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OFFICE OF RESEARCH ADMINISTRATION

RESEARCH PROJECT INITIATION

Date: April 9, 1973

Project Title: Comparative Evaluation of Solar, Fission, Fusion, and Fossil Power Systems

Project No: E-25-633 and E-26-606

Mech. Nuc.

Principal Investigator Dr. J. R. Williams and Dr. J. D. Clement

Sponsor: NASA - Lewis Research Center; Cleveland, Ohio

Agreement Period: From March 1, 1973 Until August 31, 1973

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NOTE: Follow-on projects to E-25-624 & E-26-605.

Assigned to: School of Mechanical Engineering & School of Nuclear Engineering

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OFFICE OF RESEARCH ADMINISTRATION

RESEARCH PROJECT TERMINATION

Date: February 5, 1974

Project Title: Comparative Evaluation of Solar, Fission, Fusion, & Fossile Power Systems

Project No: E-25-633 and E-26-606

Principal Investigator: Dr. J. R. Williams & Dr. J. D. Clement

Sponsor: NASA - Lewis Research Center; Cleveland, Ohio

Effective Termination Date: 9/30/73 (Final Report due at latest)

Clearance of Accounting Charges: All allowable charges should have been cleared.

Grant Closeout Items Remaining: Final Fiscal Report
Final Report of Inventions
~~Final Equipment Inventory, etc.~~ Submitted 17 Sep 73

School of ME & NE

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E-25-633/E-26-606

FINAL REPORT

NASA Grant NGR-11-002-166

COMPARATIVE EVALUATION OF SOLAR, FISSION, FUSION, AND FOSSIL ENERGY RESOURCES

PART I

SOLAR ENERGY

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SOLAR ENERGY: ITS TIME HAS COME

In 1970 the total energy consumed in the United States was about 65×10^{15} Btu[1], which is equal to the energy of sunlight received by 4300 square miles of land, or only 0.15% of the land area of the continental U.S. Thus, even if this energy were utilized with an efficiency of only 10%, the total energy needs of the U.S. could be supplied by solar collectors covering only 1.5% of the land area, and this energy would be supplied without any environmental pollution. With the same 10% utilization efficiency, about 4% of the land area would supply all the energy needs in the year 2000. By comparison, at present 15% of the U.S. land area is used for growing farm crops.[2] For some applications, such as heating water and space heating for buildings, the utilization efficiency can be much greater than 10%, and the collectors located on vertical walls and rooftops of buildings, so the 4% estimate represents an upper limit and actual land area requirements may be considerably smaller.

As a practical matter, even though sunlight can provide all our energy needs without pollution, in the forseeable future solar energy will not provide all or even most of this energy. Over the past century fossil fuels have provided most of our energy because energy from fossil fuels has usually been cheaper and more convenient than energy from available alternative energy sources, and until recently environmental pollution has been of little concern. The construction of large nuclear electric generating plants is presently underway, and nuclear power will play an increasingly important role ; so in the coming decades a variety of energy sources will supply the U.S. energy needs, and solar energy will only be utilized when it is competitive with alternative energy sources.

Over the past few years, energy forecasts[3-12] have been made which predict large increases in the consumption of oil and coal as well as a rapid increase in nuclear generation. However, these forecasts predict that the domestic production of oil would not be sufficient to keep pace with demand, so large increases in oil imports would be necessary. The recent oil embargo and rapid escalation of the cost of foreign crude oil has cast doubt on the ability of the U.S. to supplement its energy needs from foreign imports, so the President has urged that the U.S. become self sufficient in its energy supplies by 1980. This will require rapidly developing additional domestic energy resources. Solar energy, which so far has seen insignificant use in the U.S., can be rapidly utilized to make a significant impact as a new energy resource over the next few years. The most immediate large-scale applications would be the heating and cooling of buildings, heating water, and supplying heat for industrial and agricultural drying operations. Over the longer term, solar energy can also be used for pollutionless electric power generation.

The NSF/NASA Solar Energy Panel[13] identified three broad applications as "most promising from technical, economic, and energy quantity standpoints. These are: (1) the heating and cooling of residential and commercial buildings, (2) the chemical and biological conversion of organic materials to liquid, solid, and gaseous fuels, and (3) the generation of electricity". It also reported that "solar energy can be developed to meet sizable portions of the Nation's future energy needs". Energy for space heating, air conditioning and water heating for buildings presently accounts for about 22% of the total energy consumption in the U.S.[14], and virtually all this energy is supplied by the combustion of high quality fossil fuels. Solar heat could provide about half this energy, and supply it more economically[15].

AVAILABILITY OF SOLAR ENERGY

In order to evaluate the economics and performance of systems for the utilization of solar energy in a particular location, a knowledge of the available solar radiation at that place is essential. Thus, the utilization of solar energy, as with any other natural resource, requires detailed information on availability.

For approximate calculations, average values of energy availability are often used. Cherry[16] discusses solar energy availability as follows: "Availability of Solar Energy: Solar energy arrives on the surface of the U.S. at an average rate of 1500 BTU/ft^2/day (about 42 x 10^9 BTU/mi^2/day). Over the period of a year a square mile receives about 15 x 10^{12} BTU. In 1970 the total energy consumed by the U.S. for all purposes was about 65 x 10^{15} BTU.[1] Thus 4300 sq. mi. of continental U.S. land receives on the average in one year the equivalent of all the U.S. energy needs! At 10% conversion efficiency 43,000 sq. mi. - about 1.5% of the land area of the 48 contiguous states - could produce the amount of power the U.S. consumed in 1970". Boer[17] describes solar energy availability as "a double periodic function with a 24 h and a 365 d period length, superimposed with a fluctuating screening function (cloud cover). The maximum amplitude of this function is approximately 1 KW/m^2 and for the continental U.S.A., it integrates to an average energy influx of approximately 1800 KWh/m^2 year". As a rule-of-thumb, the yearly average solar energy received in the United States is about 60 BTU/ft^2 hr.

However, precise evaluation of proposed solar energy systems requires accurate data on the solar intensity, spectrum, incident angle, and cloudiness as a function of time, at the place where the solar energy system is to be located. Past surveys of worldwide solar radiation (insolation) have been based on very limited data for most areas. A large amount of data is available in the United States and Japan on the time dependent direct and diffuse intensity function. Many solar applications require data on the probability of cloudy periods of specific duration, and this type of data is seldom available. Also, in some cases the results of radiation surveys are reported on an annual basis only, which precludes the use of this information for the rational design of solar energy systems in most areas where seasonal variations of radiation are large.

Lof[18] conducted a survey of world solar radiation and compiled data from many sources . He described several types of solar radiation data, including "direct radiation at normal incidence, direct plus diffuse radiation at normal incidence, direct radiation on a horizontal surface, direct plus diffuse radiation on a horizontal surface, and each of these on tilted and on vertical surfaces. For each type of measurement, there are also the possible choices of maximum and minimum values in selected periods of time. Finally, it is necessary to decide on what sort of averaging should be employed; seasonal, monthly, daily, or hourly. For devices employing focusing systems, normal incidence of direct radiation would of course be preferred. For flat-plate systems, it would be preferable to have total (direct plus diffuse) radiation on a sloping surface if the collector is to be used in that position. Some design purposes would best be served by use of maximum radiation values; whereas, performance over a period of time might be determined most readily by an appropriate mean radiation figure and a distribution parameter. No single type of data or method of compiling will serve all needs.

The form of the data most available and most frequently reported is total radiation (direct plus diffuse) on a horizontal surface received each day or in some cases each hour. This is, moreover, probably the most generally useful form of radiation data, as methods are available for estimating other types from these figures". The types of instruments used to measure this data are also described.

"Solar radiation is measured by several different types of instruments having various characteristics and degrees of accuracy. With few exceptions, radiation-measuring instruments in use are of two main types: the thermoelectric type and the bimetallic expansion type. Each of these has variations. The thermoelectric types include the Kimball pyranometer (manufactured by Eppley) and the Moll-Gorczynski pyranometer (manufactured by Kipp and Zonen). A difference in temperature of black and white surfaces in a glass-enclosed chamber is caused by solar-radiation absorption; the electric output from thermopiles in these units is usually recorded on some type of chart or totalled by means of an integrator. If well calibrated and maintained, these instruments can provide daily totals of solar and sky radiation usually within three percent of true values; most recorded data are probably less accurate.

The principal radiation meter of the bimetallic expansion type is the Fuess-Robitzsch pyranometer or pyranograph (with self-contained recorder). In this instrument, differential expansion of a metallic element due to solar absorption causes the movement of a stylus on a clock-driven chart. Its accuracy is lower than the thermoelectric types, deviations of ten percent from true value not being uncommon. Another meter of this type is the Michelson pyranometer.

Unless a pyranometer is provided with some type of integrator, the common method for obtaining hourly and daily total radiation values is by planimetry from the chart records.

Another radiation instrument used by a few stations is the Bellani pyranometer, which provides an indication of total solar radiation by the quantity of a liquid that has distilled from a solar-heated evaporating chamber. Periodic measurement of the distilled liquid permits estimation of the incident radiation during the interval.

In the United States, the Eppley pyranometer is most frequently used, whereas in Europe and Africa, the Kipp is more common. The Robitzsch bimetallic type is simpler and cheaper, and fairly widely used in South America and Asia, as well as in scattered stations elsewhere in the world.

The other type of data used in this study is the percentage of possible sunshine or the hours of sunshine per day as measured by the Campbell-Stokes sunshine recorder. This instrument employs a spherical lens to focus direct sunshine onto a paper chart. Discoloration of the chart occurs, due to heat, whenever the solar disc can be seen. The length of the discolored line divided by the total length of the chart corresponding to the time between sunrise and sunset is the percent possible sunshine for the day. This instrument is widely used and is actually a standard for this type of measurement."

Regular measurements of sunshine duration and cloudiness are made at numerous weather stations throughout the world, and these records usually cover periods of 20 to 60 years or more. The average daily radiation is a function of sunshine duration at the particular location, and is correlated with the amount received outside the atmosphere Q_o by

$$Q = Q_o \left(a + b \frac{S}{S_o}\right)$$

where Q is the average daily radiation received at the surface location, S is the number of hours of sunshine recorded at the site per day, and S_o is the maximum number of hours of sunshine that are possible at the site per day (unobstructed horizon), and a and b are constants. This relationship is based on work by Angstrom.[19] Lof[18] gives values of a, b and S/S_o as follows:

TABLE 1 - CLIMATIC CONSTANTS

Location	S/S_o	a	b
Charleston, S.C.	0.67	0.48	0.09
Atlanta, Ga	0.59	0.38	0.26
Miami, Fla.	0.65	0.42	0.22
Madison, Wis.	0.58	0.30	0.34
El Paso, Tex.	0.84	0.54	0.20
Poona, India (Monsoon)	0.37	0.30	0.51
(Dry)	0.81	0.41	0.34
Albuquerque, N.M.	0.78	0.41	0.37
Malange, Angola	0.58	0.34	0.34
Hamburg, Germany	0.36	0.22	0.57
Ely, Nevada	0.77	0.54	0.18
Brownsville, Tex.	0.62	0.35	0.31
Tamanrasset, Sahara	0.83	0.30	0.43
Honolulu, Hawaii	0.65	0.14	0.73
Blue Hill, Mass	0.52	0.22	0.50
Buenos Aires, Arg.	0.59	0.26	0.50
Nice, France	0.61	0.17	0.63
Darien, Manchuria	0.67	0.36	0.23
Stanleyville, Congo	0.48	0.28	0.39

The present status of solar energy availability measurements was described at the recent NSF/NOAA Solar Energy Data Workshop[20]. Ed Jessup (from NOAA) described the National Weather Service solar radiation network which has over 90 measuring sites. A few of these are "EPPLEY

Model II" sites which have twice the accuracy of the other sites. Three basic problems of many sites are equipment deterioration, inadequate monitoring and "program disorganization". These problems are being rectified. Data is stored at one minute intervals on tape. Kirby Hanson (NOAA) discussed the errors in available solar radiation data. The various primary standards that have been used differ from each other as much as 6%, so care must be taken in comparing data from different instruments. Instruments which are being used degrade by as much as 20% - 30% before being replaced, so measured intensities can be 20% to 30% low for this reason. Some sites, however, have very good data with an accuracy of 2 to 3%. R. Himberger (NOAA) described the availability of data, and the form that is available from the National Weather Service. Much of the data is hourly data on tape or cards, and a data format manuel is also available. Hourly or daily data are no longer published in printed form at the national level, but only in card, tape or microfilm form. Differences between monthly average sunshine may differ about 40% from year to year and typically 20% to 30% from site to site. There may be large differences between nearby sites due to local weather differences. Also, there can be sizeable differences from year-to-year because of changes in atmospheric turbidity.

Efforts are underway to relate reflected solar radiation to ground level incident radiation so that satellite measurements can be made useful for terrestrial solar energy generation. Absolute deviation of measurements of the solar constant vs. wavelength is less than 5%, using spectral radiometers. Surface albedo is determined by taking the 15 day minimum value of reflected sunlight measured by the satellite, and once this value is determined, it can be used to evaluate incident surface radiation from satellite measurements. Satellite measurements should provide very useful data over short time scales, but should not be extropolated over long time scales because of variations in surface albedo and atmospheric turbidity. There are several techniques for the computer enhancement of satellite pictures for the determination of insolation due to haze. Satellite measurements are essential for microscale data (resolution a few miles); interpolation between stations is not adequate for specific site studies of solar-thermal conversion, this data must come from satellites. One problem, however, is that satellites provide data on total radiation, whereas for concentrator power systems, direct beam radiation is needed. One can determine this if the cloudiness is measured, and satellites do measure cloudiness. Dr. M. P. Thekaekara (NASA/Goddard) and others at NASA made measurements of the solar spectrum and solar constant, which is 1353 + 1.5 W/m^2 outside the atmosphere.

The flat plate collector incorporates a transparent cover over a black plate with air or water flowing over or through the black plate, and is usually fixed in position. In order to evaluate their performance, one must know the intensity, angle and spectrum of solar energy as a function of time. Surface reflectivities depend on the incidence angle, and incident radiation must be split into direct and diffuse components. Liu has developed an empirical technique for doing this by using a relationship between daily total radiation outside the atmosphere to daily total at ground level.[20] He has developed a plot of hourly radiation vs. fraction of time radiation received. These statistical distribution curves are very similar for different sites of equivalent overall cloudiness. Thus far no analysis has been done on the probability of two consecuative days of cloudiness, etc., which is needed for determining storage requirements.

This type of distribution will also be about the same for different sites of the same long term average cloudiness.

Dr. Robert Schlesinger and others at J.P.L. have investigated the sensitivity of solar collector design to solar input. JPL and California Gas are evaluating the SAGE (Solar Assisted Gas Energy) system for providing hot water for apartment complexes. They determined the effect of insolation levels on collector size and cost. Water is supplied at 140°F. The flat plate collectors have 2 glass sheets over a black plate containing water tubes. Collector area vs. insolation is plotted for constant system performance. 46 ft^2/apartment unit is used on a clear summer day. A 10% decrease in solar energy results in an 18% increase in area and cost; a 30% decrease doubles collector area, and increases total system cost about 50%. He said this system is designed exclusively for Pasadena, California, so the winters are not very cold.

In the tower concept for central station power generation, about a thousand separate flat mirrors spread over a one square mile area reflect light to a centrally located boiler on a tower. Each mirror must be independently steered with a heliostat to keep it oriented so that sunlight is reflected to a tower. If a small amount of haze results in significant small angle scatterings, the performance of such high concentration ratio systems would be degraded. One problem with solar cell systems is lack of insolation data. The direct component is essential for solar cells with concentrators. Concentration ratios up to 10 are feasible. The need for spectral information is not critical as long as a photovoltaic cell of the type under consideration is used for insolation measurements. JPL calibrated solar cells on high altitude balloons. Sets of solar cells with different spectral responses can be used to obtain the necessary insolation data for predicting performance of different types of cells. The cell is characterized by measurements of its short circuit current and temperature. Tests of solar cell powered buoys for navigation have been made by the Coast Guard. Going to solar powered buoys will save about $3 million per year, mainly due to the smaller number of trips out to the buoys for servicing. The solar cells are purchased from Heliotech, Centralab, Solar Power Corp (Exxon), and Sharp. Spectral as well as total insolation data are required for testing solar cells and cover materials. Covers cost from 0.1¢/ft^2 to 25¢/ft^2 depending on material. Some materials, like mylar, will degrade in the U.V. up to 0.4 microns; PVC plastic is sensitive to degradation by short wavelength UV. Transmission in the area of 0.4 microns may be important for new types of cells with short wavelength response. There is considerable uncertainty at present in insolation between 0.3 and 0.45 microns.

SOLAR ENERGY COLLECTORS

The type of device used for the collection of solar energy depends primarily on the application. Flat plate thermal energy collectors are used for heating water and heating buildings, but can provide temperatures of only about $100^{\circ}F$ above ambient. If higher temperatures are desired, the sunlight must be concentrated onto the collecting surface. If electrical power is to be produced, photovoltaic cells can be used to convert sunlight directly into electricity, either with or without concentrators. The decision as to what kind of collector to use for a specific application is dictated by economics.

Flat Plate Collectors

Figure 1 illustrates the basic components of a flat plate collector. A black plate is covered by one or more transparent cover plates of glass or plastic, and the sides and bottom of the box are insulated.

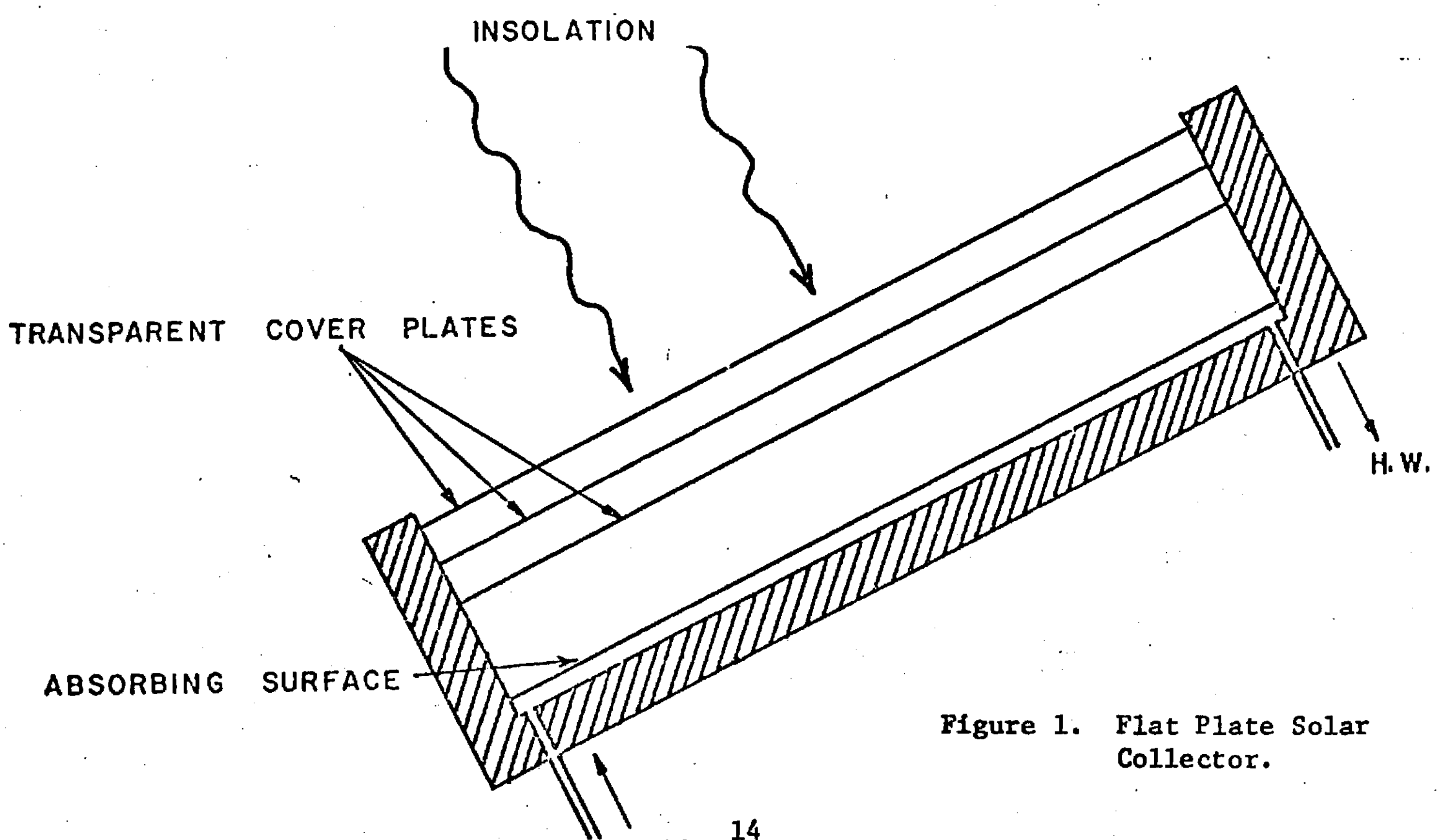


Figure 1. Flat Plate Solar Collector.

Sunlight is transmitted through the transparent covers and absorbed by the black surface beneath. The covers tend to be opaque to infrared radiation from the plate, and also retard convective heat transfer from the plate. Thus, the black plate heats up and in turn heats a fluid flowing under, through, or over the plate. Water is most commonly used, since the temperatures involved are almost always below the boiling point of water. The hot water may be used directly or may be used for space heating in homes and buildings. Kakabaev[21] tested five types of flat plate collectors and showed that the collection efficiency ranged from 40% to 60% for a 30°F temperature rise and dropped to 30% or less for a 100°F temperature rise. His collectors consisted of a wood frame with the flat black collector inside. 7 to 10 cm of sawdust were used beneath the collecting surface for insulation, and the top of the frame was covered with a single 2 mm thick window glass. The collector was a 1m x 3m steel sheet of 2.2 mm thickness containing 1 cm diameter coolant tubes 10 cm apart. The maximum incident radiation intensity was 800 Kcal/m^2 hr.

Lorsh[22] tested a collector consisting of two glass panes and a flat black metallic absorber and studied the effects of varying the air gap and the surface coating. Using air gaps between the glass panes and between glass and collector plate of 0.01, 0.02, 0.04 and 0.08 feet, he found that the best performance was with the 0.08 foot spacing, but the performance with the 0.04 foot spacing was almost as good. The performance of these collectors was considerably improved when a selective coating was applied to the collecting surface instead of flat black paint. Figure 2 illustrates the spectral reflectance of three types of coatings.[23] Such coatings strongly absorb incident sunlight, but retard

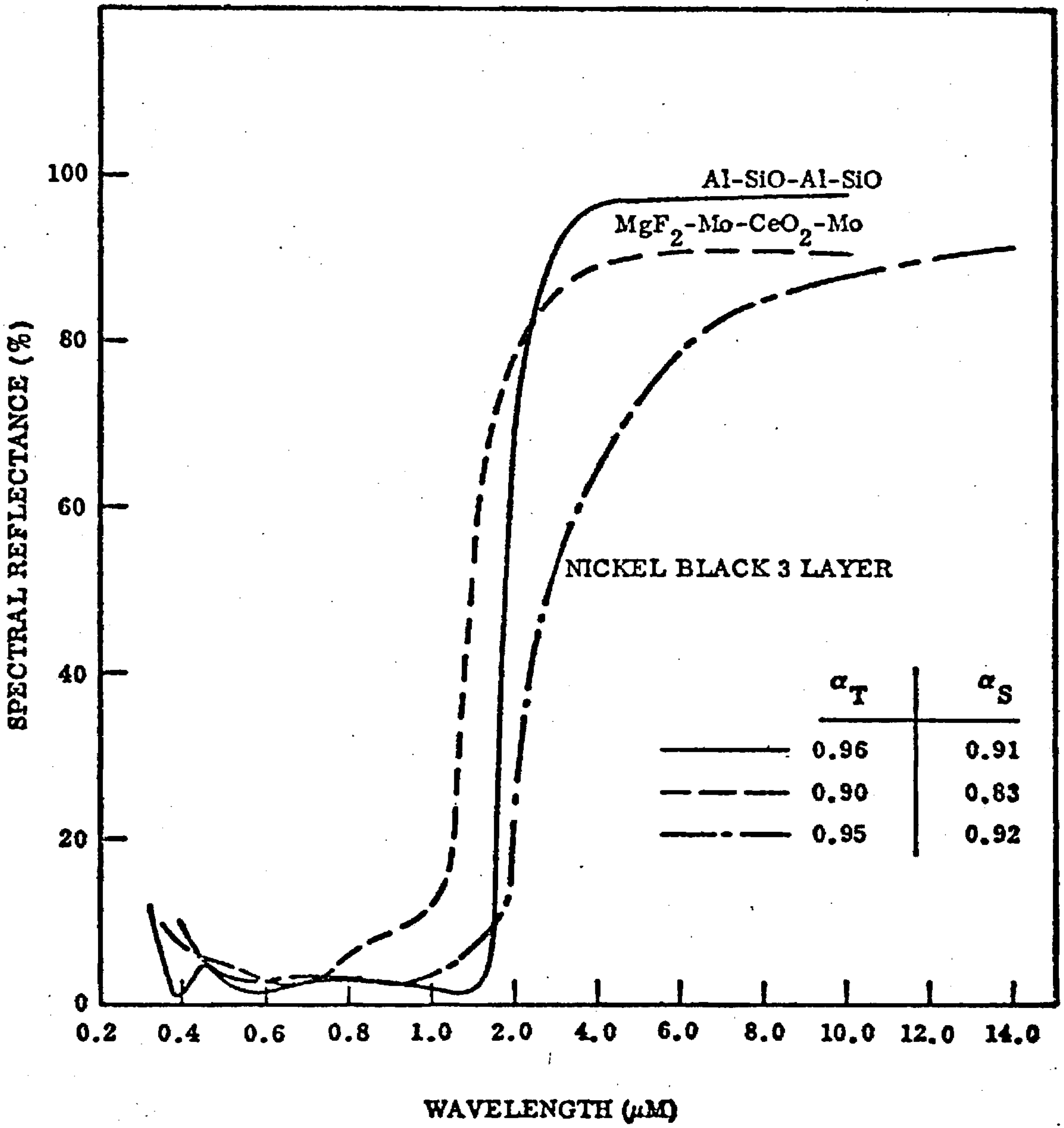


Figure 2. Spectral Reflectance of Spectrally Selective Coatings.[23]

reradiation of infrared heat, and thus allow the collecting surface to reach a higher equilibrium temperature. For a 100°F temperature difference between the outer glass and absorber the collection efficiency increased from 35% to 55% when the selective coating was added, and increased from 10% to 40% when the temperature difference was 150°F. However, the cost of the collector is also increased, so there was no major change in its cost effectiveness. The collection efficiency of duel glass plate vertical collectors was measured as a function of temperature for three insolation levels. The maximum temperature difference reached was 87°F for an insolation of 100 BTU/ft^2 hr., 153°F at 200 BTU/ft^2. hr., and 210°F at 300 BTU/ft^2 hr. The collection efficiency was about 50% at half the maximum temperature, and decreased almost linearly to 0 at the maximum temperature.

The efficiency of flat plate collectors can also be improved by anti-reflective coatings on the transparent covers. Figure 3 illustrates

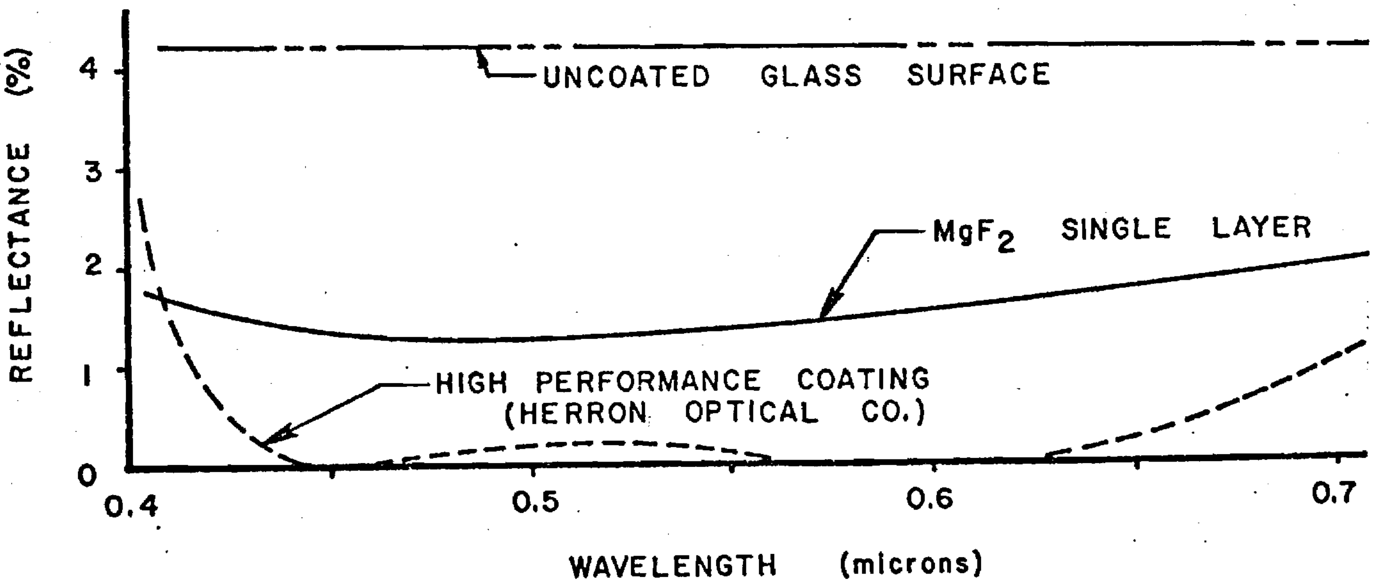


Figure 3. Reflectance of Anti-Reflective Coatings.[24]

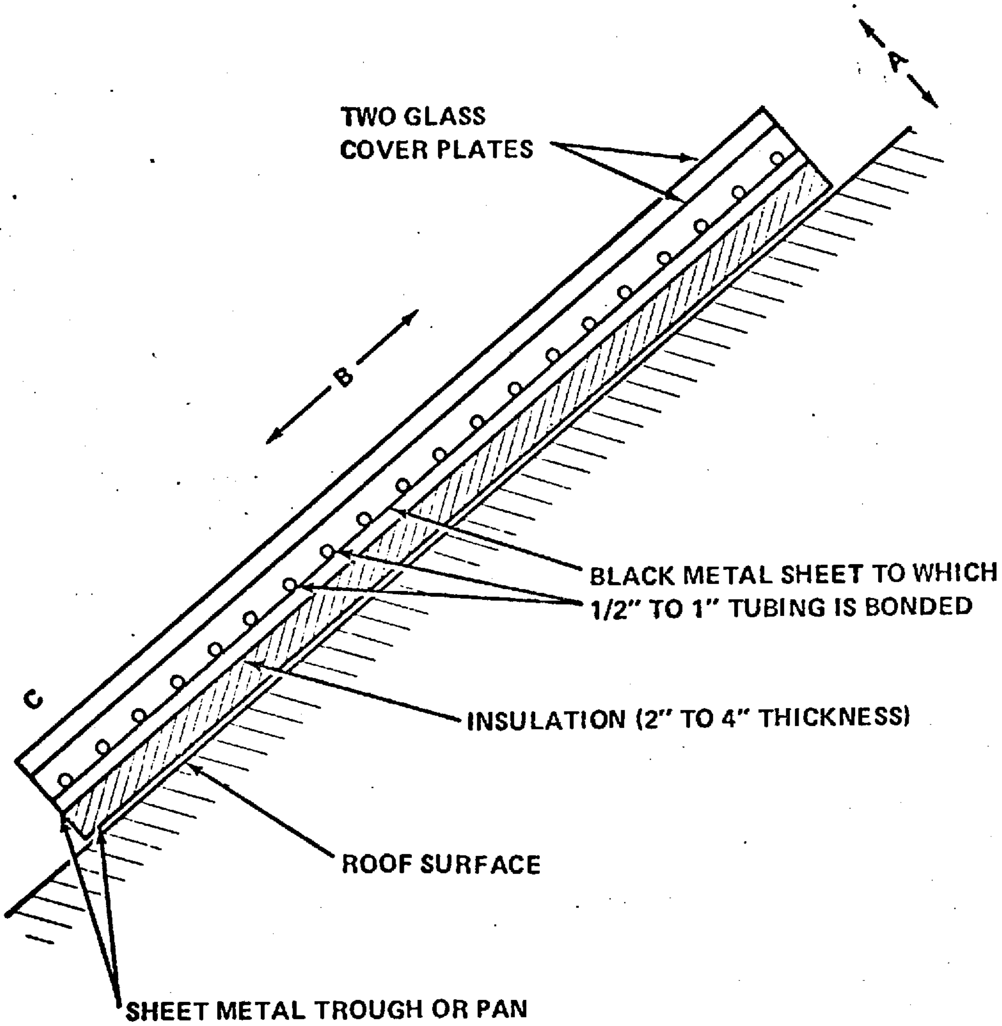
the percent of normal incidence sunlight reflected from uncoated and coated glass surfaces. Coated surfaces, of course, cost more than uncoated surfaces, and the coating cost increases as the performance increases.

Figure 4 illustrates a typical flat plate collector used to provide hot water for space heating and the operation of absorption-type air conditioners. Such collectors are placed on rooftops with a southward slope and on south-facing walls. The average daily insolation is reduced about 20% between November 21 and January 21 if the wall faces southeast or southwest instead of south, and is reduced about 60% if the wall faces east or west.[22] A flat plate collector incorporating solar cells has been developed at the University of Delaware[25] (Figure 5) to supply both electricity and heat for a house. One problem with this type of collector is the decrease in photovoltaic conversion efficiency and lifetime with increasing temperature. The 4 x 8 foot collectors are deployed between the roof joists from the inside; the outside is glased with 1/4 inch plexiglas. The heat transfer fluid for this type of collector is air.

Solar Concentrators

Concentrators are used to produce temperatures in excess of about 250°F for efficient electrical power generation, for industrial and agricultural drying operations, and for other applications where high temperature heat is needed. Also, concentrators have been used to increase the power output of photovoltaic cells.[26]

For high concentration the ideal form of the concentrator, from an optical standpoint, is parabolic; however in order to achieve this high concentration the reflector must be steered so as to be kept directed toward the sun, and the heat exchanger must be kept located at its focus. For this reason, parabolic concentrators are seldom considered for most solar energy applications. Large solar collectors are subject to large wind loadings, and thus require a sturdy supporting structure. The analysis of such parabolic concentrators has been discussed in detail by Teplyakov[27].



NOTES: ENDS OF TUBES MANIFOLDED TOGETHER
ONE TO THREE GLASS COVERS DEPENDING
ON CONDITIONS

DIMENSIONS: THICKNESS (A DIRECTION) 3 INCHES TO 6 INCHES
LENGTH (B DIRECTION) 4 FEET TO 20 FEET
WIDTH (C DIRECTION) 10 FEET TO 50 FEET
SLOPE DEPENDENT ON LOCATION AND ON
WINTER-SUMMER LOAD COMPARISON

Figure 4. Flat Plate Collector for Heating Water.[13]

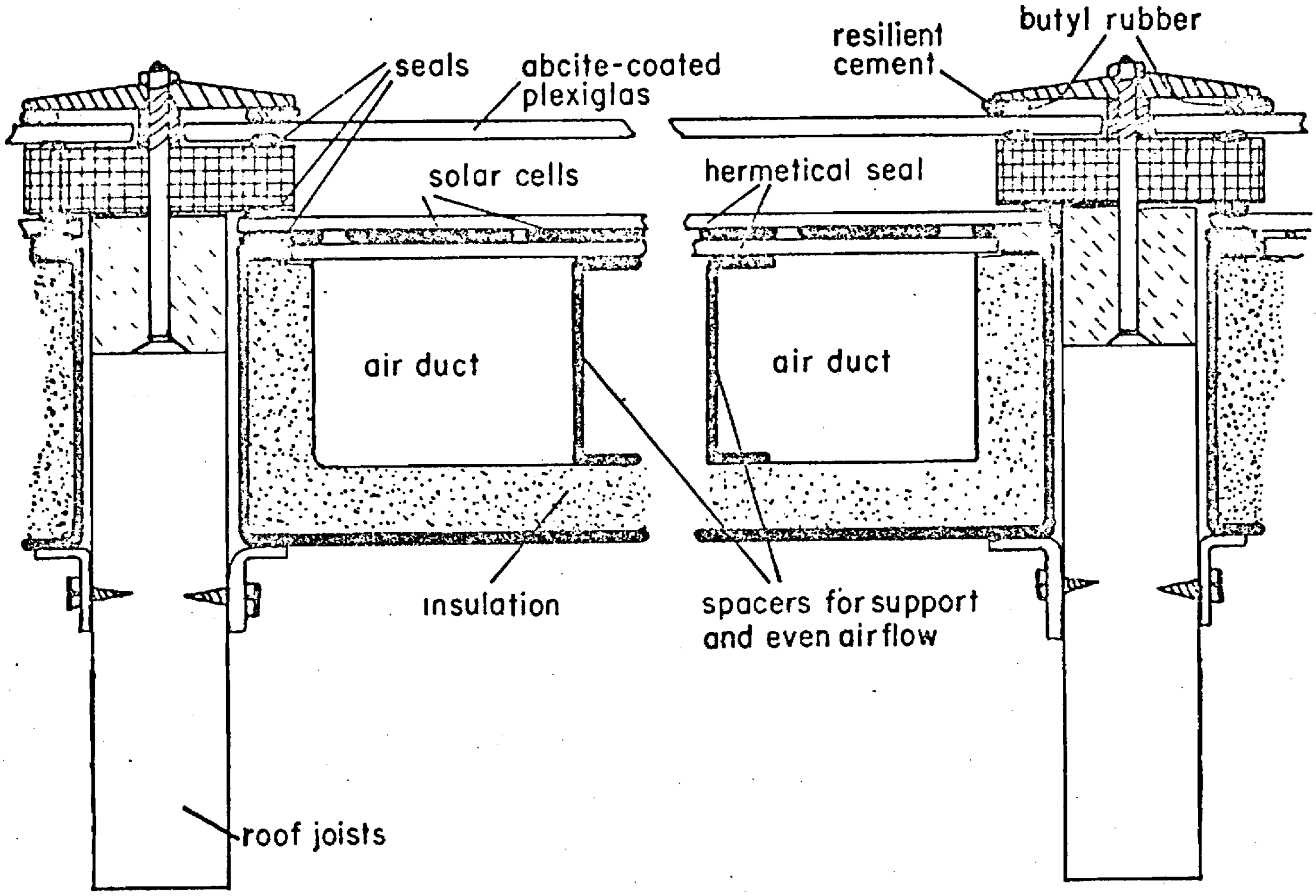


Figure 5. Cross Section of Flat Plate Collector Containing Solar Cells.

High performance concentrators can also be built using toroidal, flat or spherical components which are much cheaper to produce.[28]

One simple type of concentrating solar collector (Figure 6) uses a parabolic cylinder reflector to concentratate sunlight onto a collecting pipe within a quartz or pyrex envelope. The pipe can be coated with a selective coating (Figure 3) to retard infrared emission, and the transparent tube surrounding the pipe can be evacuated to reduce convective heat losses. The reflector is steered during the day to keep sunlight focused on the collector. This type of concentrator, known as the parabolic trough concentrator, cannot produce as high a temperature as the parabolic reflector, but produces much higher temperatures than flat plate collectors.

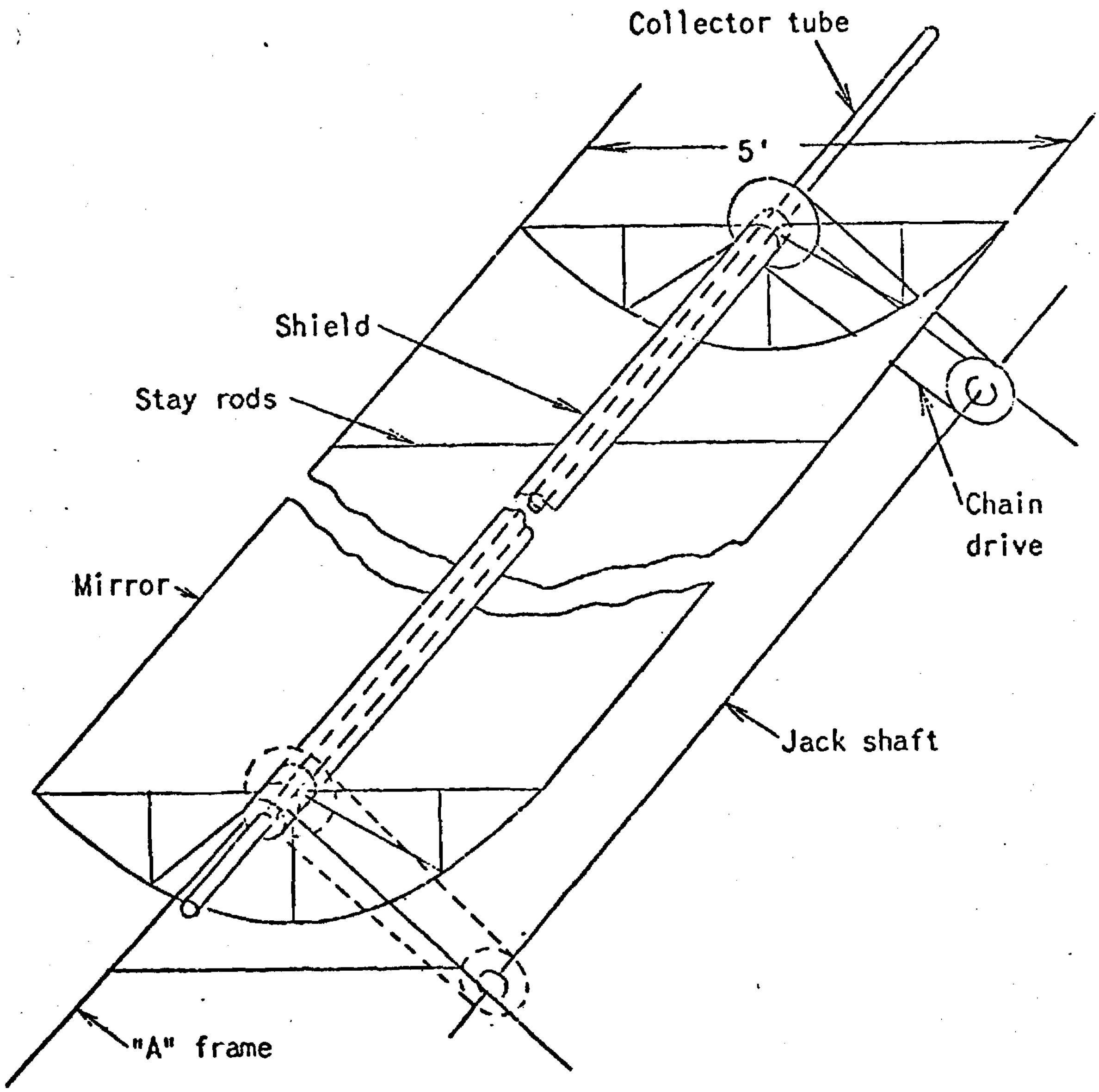


Figure 6. Parabolic Trough Concentrator.

Eibling[29] divides all solar-thermal collectors into three general categories: (1) low temperature flat-plate collectors with no concentration, (2) medium temperature concentrating collectors typified by parabolic cylinders, and (3) high concentration, high temperature collectors such as parabolic concentrators or concentrators composed of many flat mirrors focused at the same point. The following table gives the usual temperature ranges and the collection efficiencies for these three categories of collectors. The actual temperature obtained will

Table 2. Classification of Solar Collectors

Category	Example	Temp. Range	Efficiency
No Concentration	Flat Plate	150-250°F	30-50%
Medium Concentration	Parabolic Cylinder	300-800°F	50-70%
High Concentration	Parabodial	500-1200°F	60-75%

depend on the optical performance of the reflector, the accuracy of the tracking device, and the absorption efficiency of the receiver.

Lidoreko[30] and his colleagues in the Soviet Union have developed a technique for mass producing inexpensive faceted solar concentrators which form an approximate parabolic cylinder. They used a jig containing a number of vacuum socket facet holders, arranged along a convex cylindrical parabolic surface, all connected to a central vacuum system. In making a concentrator, the 26 mirror strips were placed face down on the correctly positioned holders and the vacuum held the mirror facets in the desired position throughout the manufacturing process. The reverse side of the mirrors was then coated with a layer of epoxy resin and covered with glass fabric. The supporting structure, which had the approximate surface shape of the finished concentrator, was placed on the glass fabric and glued to the mirror. After the epoxy had cured, the vacuum was turned off and the finished concentrator removed.

The Soviet researchers manufactured 80 concentrator sections one meter long and about one meter wide using this technique. These concentrator sections were used to make 2 power plants. It was only necessary to align the sections, and not the individual facets. They demonstrated that these concentrators were cheap to produce, had good optical characteristics, and were quite strong.

Three general approaches have been taken to try to reduce or eliminate the expense and technical difficulties associated with steering the reflecting surface: 1) develop simple, reliable, automatic steering mechanisms, 2) develop concentrators using a large number of separate reflectors, which require less supporting structure than a single large concentrator, and 3) develop fixed mirror concentrators.

One of the most promising passive steering devices for cylindrical-type concentrators and other small collectors is the thermal heliotrope, as described by Fairbanks and Morse.[31]

"In its most elemental form, the thermal heliotrope consists of a single bimetallic coil with appropriate thermal coatings and a feedback shade. This is shown schematically in Figure 7. The fixed end of the helix is attached either to the vehicle in a space application, or to a stationary support in the terrestial application. The solar array and the feedback shade are attached to the free end of the helix. The function of the shade is to regulate the amount of solar radiation incident on the helix, thereby causing the rotation of the helix to stop when the array is aligned normal to the solar vector.

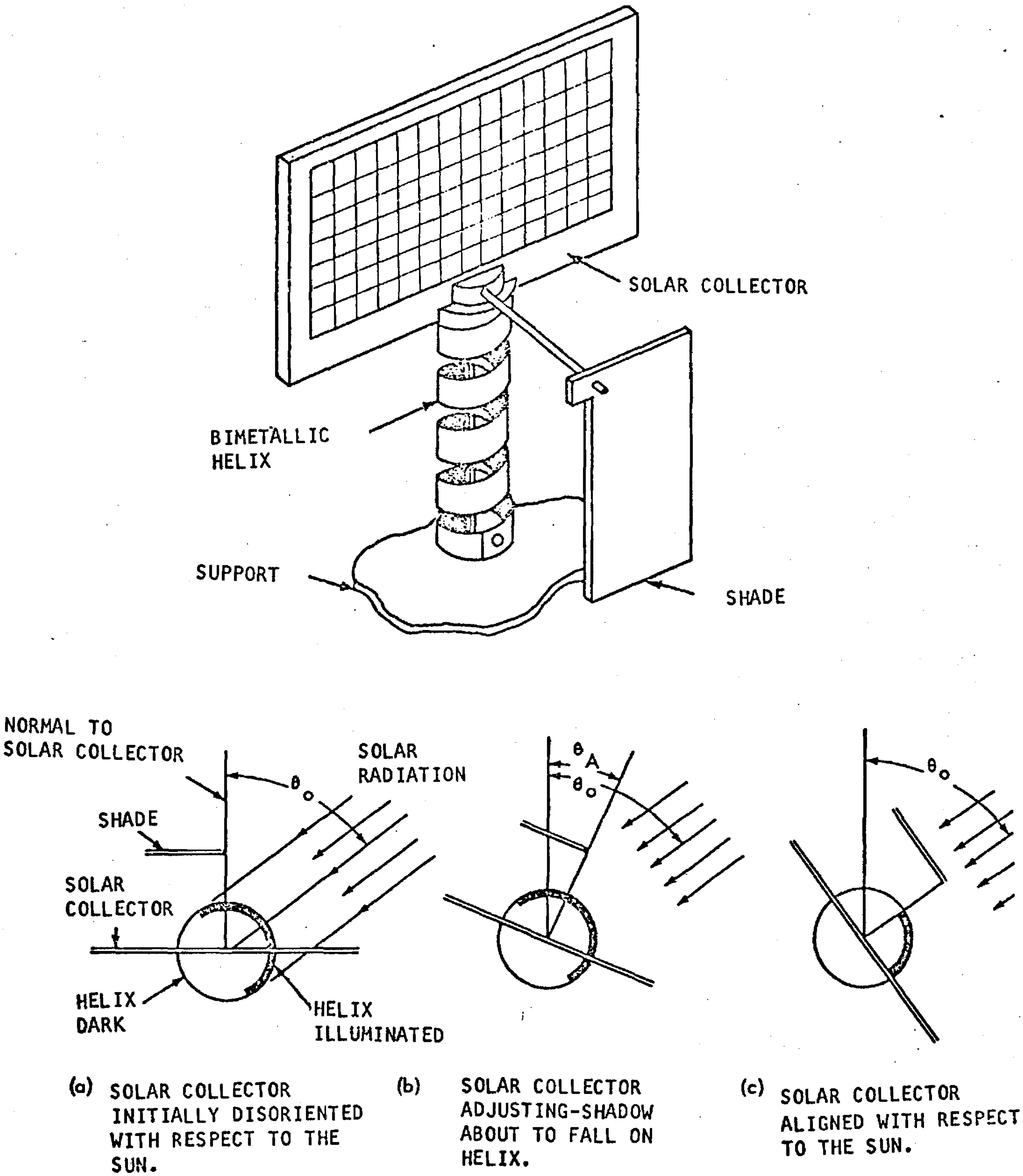


Figure 7. Thermal Heliotrope Orientation Sequence.[31]

The principle of operation may be illustrated by assuming that the sun's rays initially are at some angle θ_o with the normal to the solar cells, as shown in Figure 7a. Solar energy input to the helix causes its temperature to rise which, in turn, causes the two components of the helix to rotate - the rate and extent of rotation depending on the properties of the two components of the helix and the temperature distribution within the helix. The rotation of the free end is such that the solar array to which it is attached rotates toward the sun as shown in Figure 7b. At some angle θ_A the shade begins to cast a shadow on the helix. Further rotation of the helix causes the shade to shield a portion of the helix from the solar radiation. This decreased solar energy input reduces the rate at which the temperature of the helix was increasing which, in turn, reduces the angular velocity of the helix. A point is reached at which the net energy input to the helix is zero and the rotation ceases. At that point the solar array is aligned perpendicular with the sun's rays, as shown in Figure 7c.

The tracking feature of the thermal heliotrope may be illustrated by the situation wherein the relative position of the sun changes such that θ_o increases slightly in a clockwise direction. This change will increase the surface area of the helix illuminated by the sun's rays. The resulting increase in temperature of the helix will cause the shade to rotate in the clockwise direction until the energy balance on the helix is restored. A similar sequence of events occurs should θ_o decrease. In such a manner the solar array is able to continuously track the sun."

The bimetal considered the prime candidate for terrestrial use has a high expansion component of 72% Mn - 18% Cu - 10% Ni and a low expansion component of 36% Ni - 64% Fe, commonly referred to as Invar. This bimetal is one of the most thermally active and one of the least expensive. The thermal heliotrope is a promising passive orientation device which could probably be produced in large quantities at low unit cost, and thus reduce the cost of tracking the sun for the collection of solar energy.

Instead of steering a single concentrator, Gunter[32] proposed a faceted solar concentrator in which the separate flat reflecting facets were rotated by a single mechanism. Each facet is rotated at exactly the same speed to keep the reflected sunlight focused on a fixed heat collecting element. Another approach is to focus many separate flat mirrors onto a single point. The difficulty with this system is that each mirror requires a separate steering mechanism, but if large numbers are used, they may lend themselves to the economics of mass production.

A third approach to reducing the concentrator cost is to fix the reflector and move the heat collecting element. The problem with this is that the standard reflecting surfaces are only in focus for one sun direction. The parabolic cylinder and parabodial concentrators are only in focus when the sunlight is incident along the axis of the parabola. Thus the problem with such fixed collectors, as proposed by Steward[33], is that the focus is severely degraded whenever the incident direction of the sunlight is significantly off axis.

Recently, a new type of reflecting surface was proposed by Russell[34] which remains in focus for any incident sun angle. It is composed of long, narrow flat reflecting elements arranged on a concave cylindrical surface. The angles of the reflecting elements are fixed so that the focal distance is twice the radius of the cylindrical surface. The focus is always sharp for parallel light of any incident direction. The point of focus lies on the reference cylindrical surface, so the heat exchanger pipe can be supported on arms that pivot at the center of the reference cylinder. This greatly simplifies the positioning of the heat exchanger.

HEATING FOR HOUSES AND BUILDINGS

The Committee on Science and Astronautics of the U.S. House of Representatives has concluded[35] that "the most promising area for the application of solar energy within the next 10 to 15 years, on a scale sufficient to yield measurable relief from the increasing demands upon fossil fuels and other conventional energy sources, is the use of solar energy for space heating, air conditioning, and water heating in buildings". As is seen from Table 3, energy for space heating, air conditioning, and water heating in building services accounts for about 25% of the total energy consumption in the United States, and is presently supplied almost totally by the combustion of high quality fossil fuels. The sources which supply this energy are depicted by Figure 8. Space heating accounts for more than half of the total residential energy consumption. Space heating alone for homes and businesses accounts for 18% of all energy consumption in the United States. In the South, where solar energy is most available, practically all residential energy comes from gas or electricity, and even in the South about half this energy is used for space heating (Figure 9). Space heating and water heating account for over 2/3 of all residential energy consumption in the South.

Flat Plate Collector Systems

A typical solar heating system employing a flat plate collector is illustrated by Figure 10. A flat plate collector located on a southward sloping roof heats water which circulates through a coil in the hot water tank, then through a coil in a large warm water tank before being returned to the collector. In most areas of the country the heat transfer fluid

Table 3. ENERGY CONSUMPTION IN THE UNITED STATES BY END USE, 1960-68

(Trillions of B.t.u. and percent per year)

Sector and end use	Consumption 1960	Consumption 1968	Annual rate of growth (percent)	Percent of National total 1960	Percent of National total 1968
Residential:					
Space heating	4,848	6,675	4.1	11.3	11.0
Water heating	1,159	1,736	5.2	2.7	2.9
Cooking	556	637	1.7	1.3	1.1
Clothes drying	93	208	10.6	.2	.3
Refrigeration	369	692	8.2	.9	1.1
Air conditioning	134	427	15.6	.3	.7
Other	809	1,241	5.5	1.9	2.1
Total	7,968	11,616	4.8	18.6	19.2
Commercial:					
Space heating	3,111	4,182	3.8	7.2	6.9
Water heating	544	653	2.3	1.3	1.1
Cooking	98	139	4.5	.2	.2
Refrigeration	534	670	2.9	1.2	1.1
Air conditioning	576	1,113	8.6	1.3	1.8
Feedstock	734	984	3.7	1.7	1.6
Other	145	1.025	28.0	.3	1.7
Total	5,742	8,766	5.4	13.2	14.4
Industrial:					
Process Steam	7,646	10,132	3.6	17.8	16.7
Electric drive	3,170	4,794	5.3	7.4	7.9
Electrolytic processes	486	705	4.8	1.1	1.2
Direct heat	5,550	6,929	2.8	12.9	11.5
Feedstock	1,370	2,202	6.1	3.2	3.6
Other	118	198	6.7	.3	.3
Total	18,340	24,960	3.9	42.7	41.2
Transportation:					
Fuel	10,873	15,038	4.1	25.2	24.9
Raw materials	141	146	.4	.3	.3
Total	11,014	15,184	4.1	25.5	25.2
National Total	43,064	60,526	4.3	100.0	100.0

Note: Electric Utility consumption has been allocated to each end use.
Source: Patterns of Energy Consumption in the United States (14)

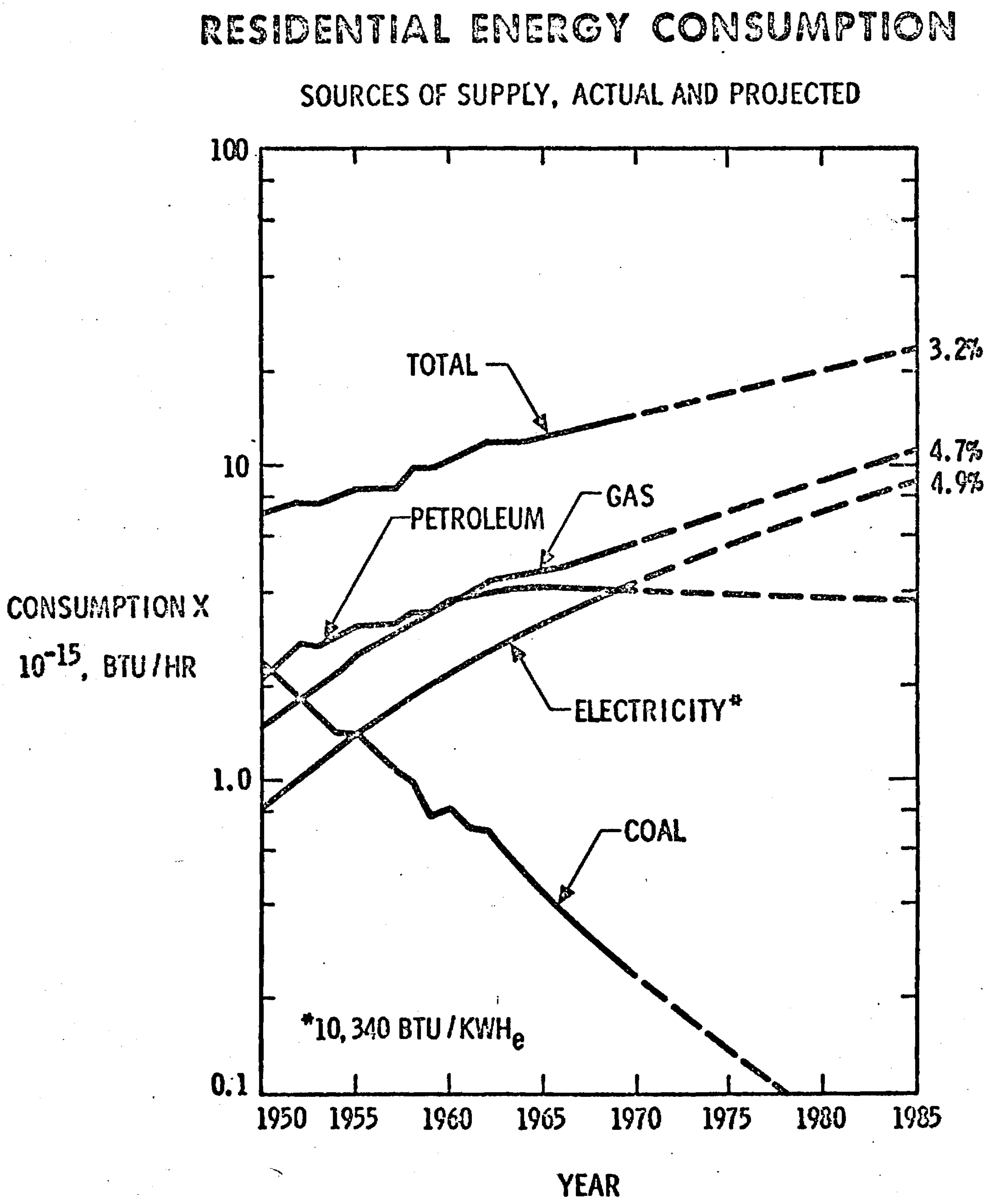


Figure 8. Sources of Residential Energy[36]

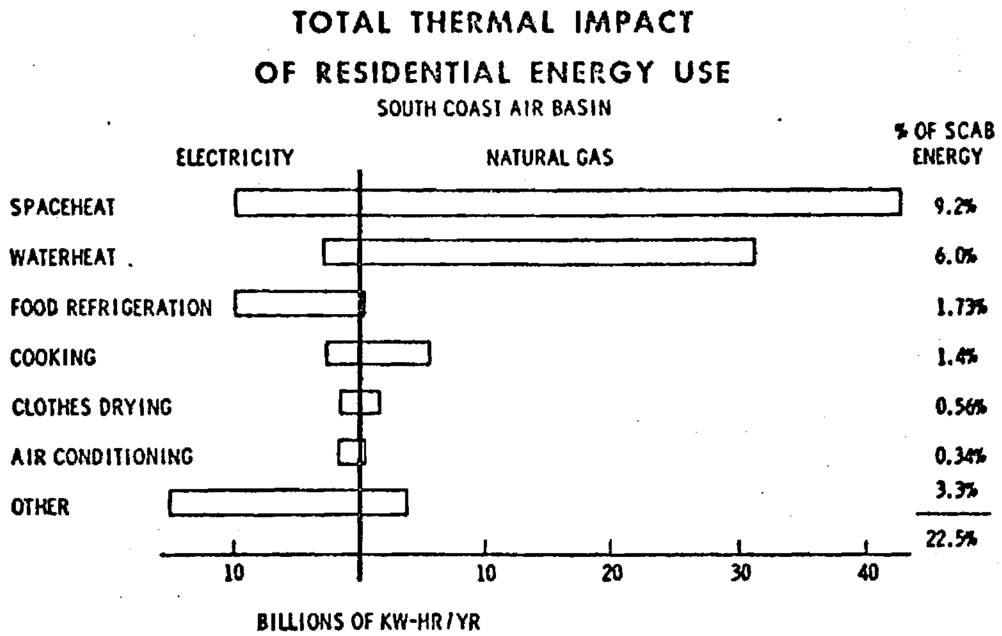


Figure 9. Residential Energy Use in the South[36]

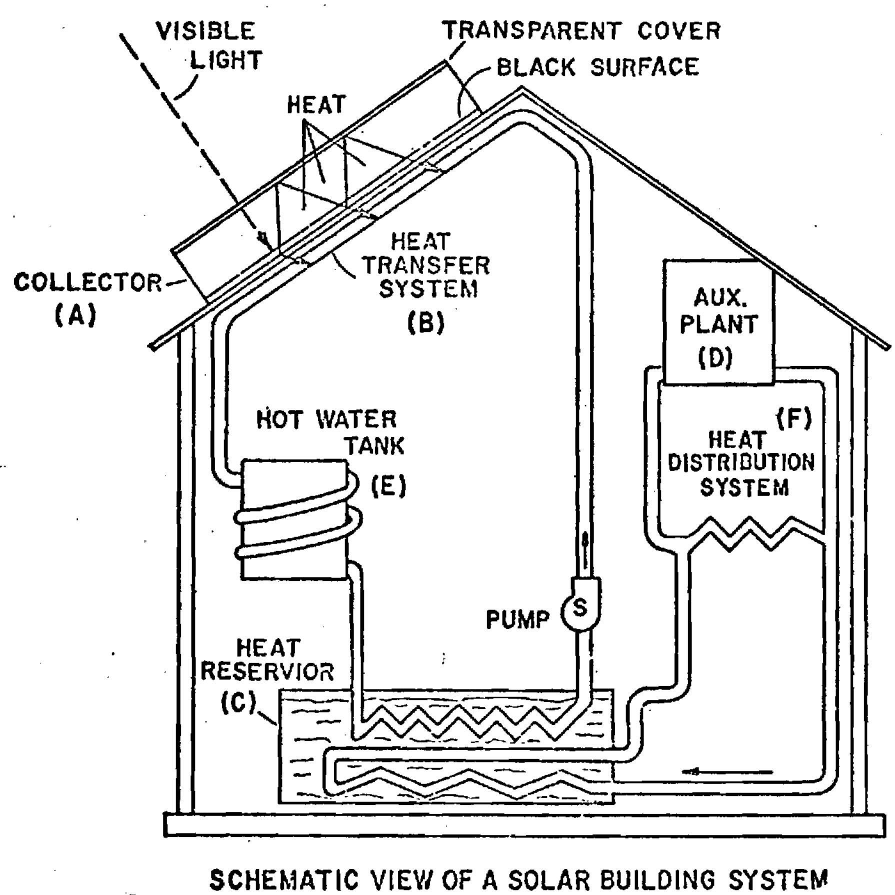


Figure 10. Solar Heating System for a Building[35]

flowing through the collector should be an anti-freeze solution to prevent freezing of the fluid in the collector tubes in the winter. The system shown in Figure 10 provides for two levels of heat storage; the hottest water which is stored in the hot water tank is used for building services, and the warm water in the large tank heats water circulating through pipes in the house. The heat reservoir for a single dwelling could be a 10 foot diameter tank, four feet deep, insulated on all sides. An auxiliary heating system is necessary to provide heat during extended cold cloudy periods when the supply of solar heat is not adequate.

Tybout and Lof[37] calculated the 1970 cost of solar space heating, and compared the cost of solar heating with gas, oil and electric heating costs by amortizing the solar system capital cost over 20 years at 6% interest. Solar heating costs were calculated for present $\$4/ft^2$ flat plate collectors and for anticipated near-term collector costs of $\$2/ft^2$. The results of these calculations for eight U.S. cities are given in the following table.

Table 4. Costs of Space Heating in 1970 Dollars/MBTU

Location	Optimized solar heating cost in 25,000 BTU/degree-day house, capital charges @ 6%, 20 years		Electric heating, usage 30,000 kwh/year	Fuel heating, fuel cost only	
	Collector @ $\$2/ft.^2$	Collector @ $\$4/ft.^2$		Gas	Oil
Santa Maria	1.10	1.59	4.28	1.52	1.91
Albuquerque	1.60	2.32	4.63	0.95	2.44
Phoenix	2.05	3.09	5.07	0.85	1.89
Omaha	2.45	2.98	3.25[3]	1.12	1.56
Boston	2.50	3.02	5.25	1.85	2.08
Charleston	2.55	3.56	4.22	1.03	1.83
Seattle-Tacoma	2.60	3.82	2.29[2,3]	1.96	2.36
Miami	4.05	4.64	4.87	3.01	2.04

Notes: [1]Electric power costs are for Santa Barbara, Electric power data for Santa Maria were not available.

[2] Electric power costs are for Seattle.

[3] Publicly owned utility.

Since these data were compiled, interest rates have increased but so have fossil fuel and electricity prices, so the general conclusions are still valid. According to Lof[15], "The two major accomplishments in this study are (1) the optimization of the design of a solar heating system and its major components, and (2) the establishment of realistic costs of solar heating in comparison with conventional heating under a variety of conditions. Both objectives have been achieved by methods which can be applied to buildings of any size and construction in any location where adequate weather data are available.

Collector size for minimum solar heat cost for a 25,000 BTU/degree day (BTU/DD) house in six locations was found to range from 208 sq ft (Charleston, S.C.) to 521 sq ft (Omaha, Nebraska), corresponding to 55 percent of the respective annual heating loads. In Santa Maria, California a 261 sq. ft. collector can supply 75 percent of the annual heat requirement. In most situations, the cost of solar heat near optimum levels is rather insensitive to collector size and the corresponding fraction of load carried. Costs rise sharply, however, if designs are based on carrying large fractions (over 90 percent) of the load. In structures having smaller or larger heat demands than 25,000 BTU/DD, optimum collector size is approximately proportional to the demand parameter.

Heat storage capacity for minimum solar heating cost in nearly all practical situations is 10 to 15 pounds of water (or its thermal equivalent) per square foot of collector. This is the equivalent to one to two days average winter heating requirement. Solar heating cost is not very sensitive to storage capacity in this general range.

Two glass covers in the solar collector yield minimum solar heating cost in nearly all locations. One cover is optimal in the warmer climates represented by Phoenix and Miami. Heating costs are the same for one or two covers in climates such as Albuquerque and Santa Maria. Collector tilt for minimum solar heat cost is 10 to 20^{o} greater than the latitude, but there is only a slight variation in cost over a range of inclinations between the latitude angle and 30^{o} higher than the latitude. Variation in thermal loss from storage (located in the heated space), within the range of practical design, has negligible effect on solar heating costs and is not a factor in optimizing design. Variation in heat capacity of the collector, within practical ranges, has negligible effect on solar heating costs and is not a factor in optimizing design.

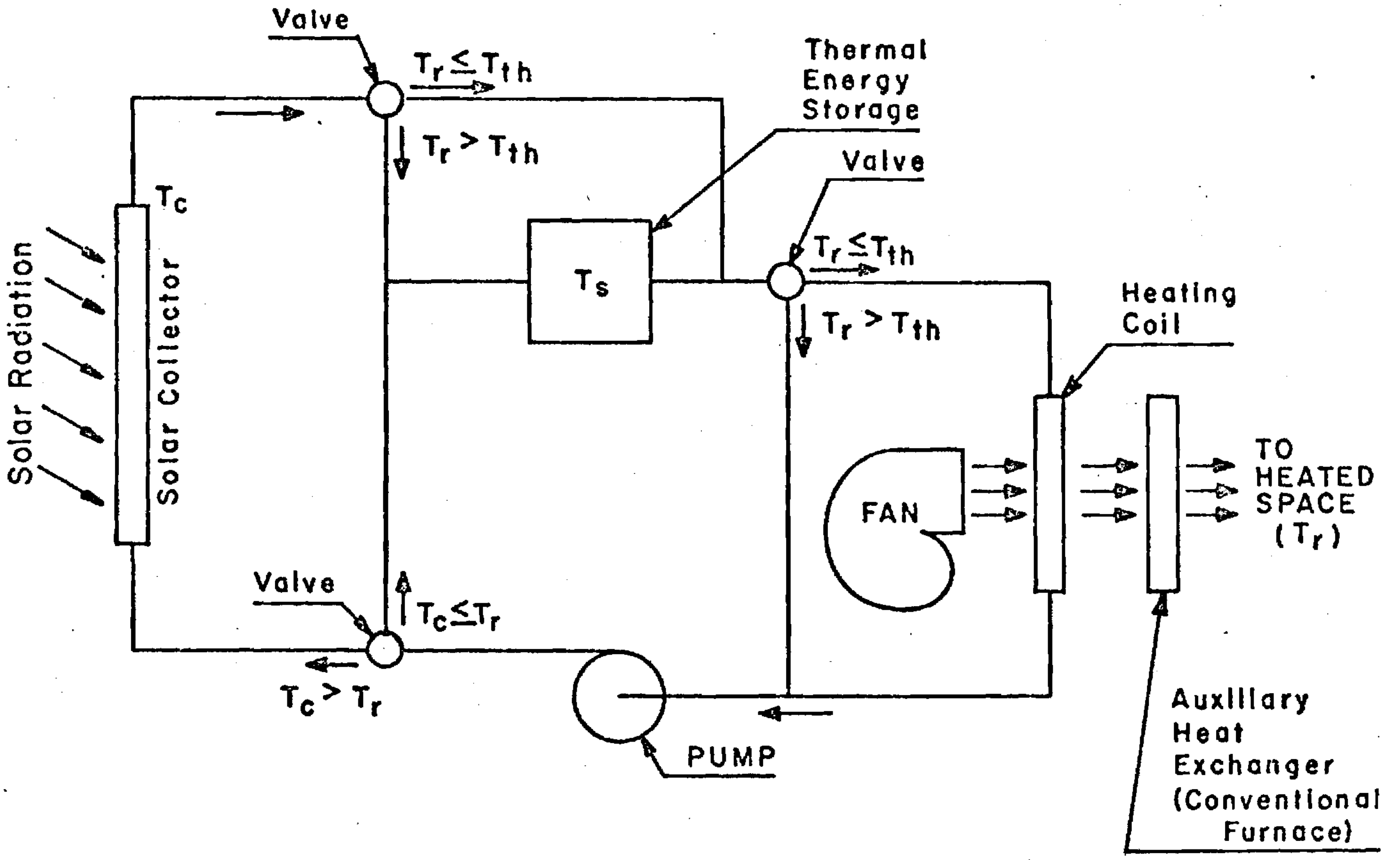
The cost of solar heat in systems of optimum design is usually in the range of two to three dollars per million BTU, and substantially below the cost of electric heat in six of the eight locations examined. Low electricity price in Seattle and low demand for space heating in Miami reverse this situation. In comparison with gas and oil heating, solar is now more expensive in six of the eight locations analyzed. But in Santa Maria and Albuquerque there are combinations of solar and fuel systems which involve total costs equal to or below those of corresponding conventional heating. In six of the eight cities there are optimum (minimum costs)combinations of solar and electric heating, the best mix being obtainable by determining marginal costs of increasing the solar heat proportion. The portion of total load supplied by solar under these conditions generally lies between 60 and 90 percent. Rising costs of heating with oil and gas are approaching solar heating costs in U.S. areas of large population. It is probable that solar heating costs will decrease somewhat as improvements are made. Competitive solar heat will become increasingly possible as these trends continue. Conditions conducive to economical solar heating are moderate to severe heating requirements, abundant sunshine, and reasonably uniform heat demand during the period when heat is needed. The higher the cost of conventional energy for heating, the more competitive a solar-conventional combination becomes".

Eibling[29] analyzed the materials cost for a flat plate collector using a single glass cover, water as the coolant, and polyurethane foam insulation, and a collector efficiency of greater than 50% at outlet temperatures up to 200°F. The materials cost on a production basis was determined to be between $1.15/ft^2 and $1.90/ft^2, (Table 5) which supports Lof's total cost estimate of $2 to $4 per square foot.

Table 5. Materials Cost for a Flat Plate Collector[29]

Component	Material	Cost $/Ft^2
Substrate/heat exchanger	Aluminum or steel	0.60 to 0.90
Cover plate	Glass	0.25 to 0.30
Thermal insulation	Polyurethene	0.25 to 0.35
Selective coatings	Oxides, coatings	0.05 to 0.35
Total		1.15 to 1.90

Several studies have been conducted to determine optimal control systems for solar home heating systems, such as the one illustrated by Figure 11. The main object of the control system is to extract heat from the solar collector when it is available, but to shut off the flow through the collector whenever the collector temperature drops below the storage temperature. In this system a separate auxiliary heater is provided. The pump circulates water through the collector whenever the collector outlet temperature exceeds the storage temperature. If the room temperature is lower than both the collector temperature and the thermostat setting, water from the collector is circulated directly



T_c = Collector temperature

T_r = Room temperature

T_s = Thermal energy storage temperature

T_{th} = Room thermostat setting

Fan Control: Same as for Conventional Heating System

Pump Control: On: $T_r < T_{th}$ and $T_c > T_r$

or: $T_r < T_{th}$ and $T_s > T_r$

or: $T_c > T_s$

Auxiliary Heater: On: $T_r < T_{th}$ and Pump is off

Figure 11. Control Circuit for Solar Heating System.[38]

through the heating pipes in the house. If the room temperature is lower than both the thermostat setting and the storage temperature, but higher than the collector temperature (such as at night), hot water from the storage tank is circulated through the room. Thus, the solar heat is transfered directly to the room if the room is too cool, and is transfered to the storage tank for later use if the room is already warm enough. This is a fairly standard type of solar thermal control system using a single water pump and three valves. The hot water coil for heating air (like an automobile radiator) can be installed in a conventional forced air furnace.

An 8000 sq. ft. solar heating building has been designed for the Massachusetts Audubon Society[39] which uses a two-pane 3500 sq.ft. flat plate collector facing south at an angle of 45°. Figure 12 shows preliminary plan and elevation sketches and Figure 13 shows the proposed solar building and the current headquarters building. Based on the results of Tybout and Lof[37] it is estimated that the flat plate collector heating system should account for between 65% and 75% of the total seasonal heating load.

Thomason[40,41] has reported results of 13 years of operation of a solar heated house which was maintained within a few degrees of 70°F year round, with up to 95% of the heat per year supplied by solar energy. As reported by Thomason, "during 13 yr. of operation, the solar energy system has supplied most of the heat requirements for the house despite half-cloudy winter weather and temperatures well below zero Centigrade (often between 0° and 32°F). Additionally a substantial portion of the domestic water heating was achieved by solar heating. Water from the 1600 gal. steel tank is pumped to the top of the solar heat collector. There it is distributed

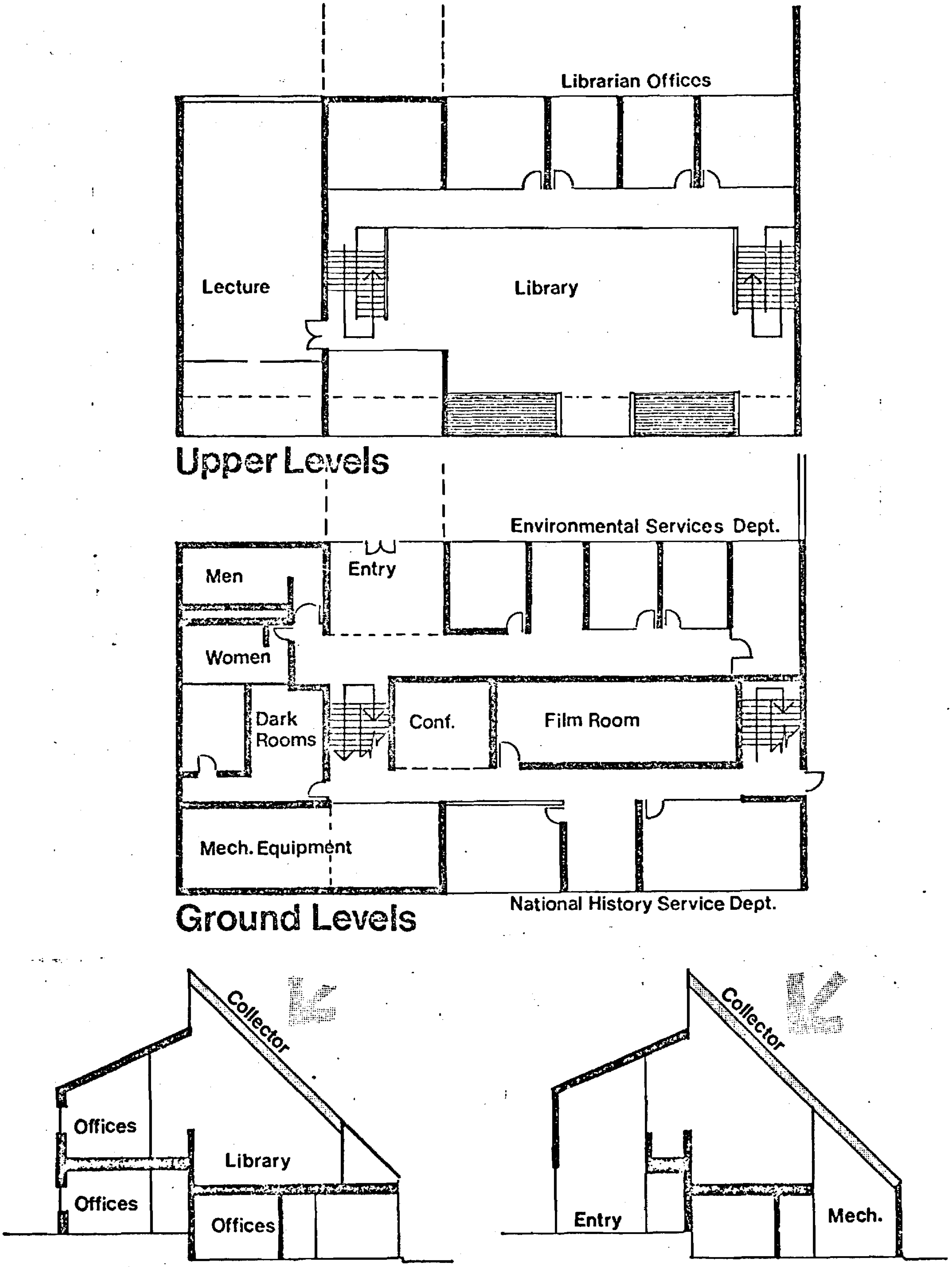


Figure 12. Plan and Elevation Sketches of Proposed Solar Building.[39]

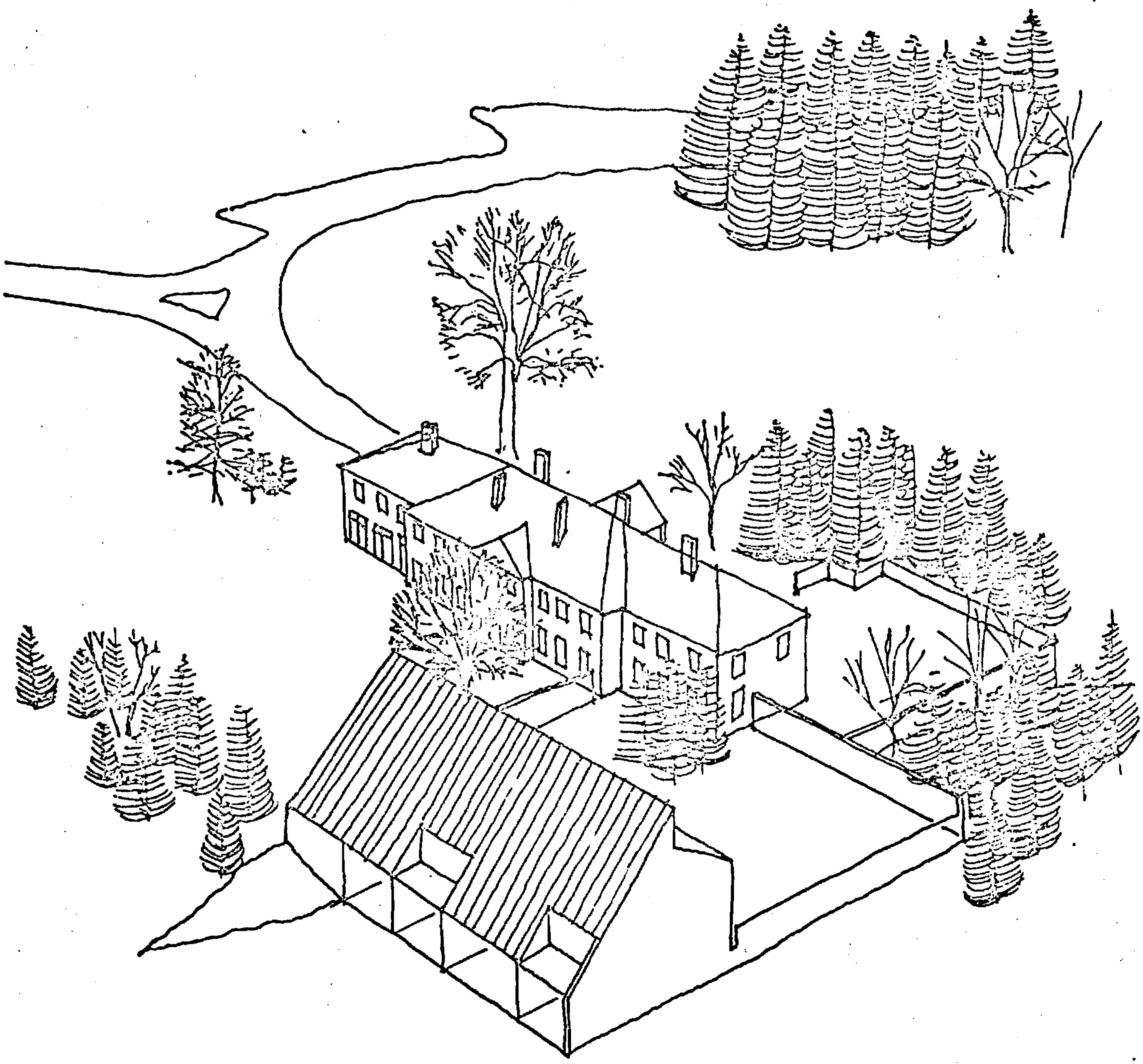


Figure 13. Proposed Solar Building and Existing Building.[39]

in small streams to hundreds of valleys on the black corrugated solar heat collector sheet. As the water flows down in the valleys it is warmed by solar energy passing through the transparent cover. A gutter at the bottom collects the small streams of warm water and passes it to a 275 gal. domestic water preheater tank and thence to the main tank in the heat storage bin. The warmed water, in addition to pre-heating the domestic water, also warms the three truckloads of fist-sized stones around the main 1600 gal. tank. Then, when the living quarters need heat, a thermostat automatically starts a 1/4 h.p. blower. This blows air through the warmed stones and around the warm tank of water thus warming the air. The warmed air passes into the living quarters. When the living quarters are warmed sufficiently, the thermostat automatically stops the blower leaving the reserve stored heat in the heat storage bin for future use. (The stored heat has kept the home temperature at $70^{\circ}F$, plus or minus $2^{\circ}F$, for about four cloudy days in mid-December). During the hot summer, water was pumped at night up to the north-sloping roof section. The tank of water and surrounding stones were thereby cooled. Then a reverse-acting thermostat turned the blower on to circulate air to the bin and thence to the living quarters to cool them".

Flat plate collectors are also used for heating air to over $100^{\circ}F$ above ambient for house heating. Water is usually used because of the simple storage system, which is just an insulated tank. Close[42] analyzed a variety of different types of air heaters. The simplest is a flat black plate covered by a transparent sheet, with air flowing in the gap between. However, higher temperatures are achieved if the air flows through or beneath the black absorbing surface, and the air gap beneath the transparent cover and plate is stagnant. A good collecting surface is a V-corrugated absorber plate with a spectrially selective coating (absorptivity 0.80 in the visible, 0.05 in the infrared). Absorbers of this type heated air to 170°F with 40% collection efficiency for an insolation of 160 BTU/ft^2.hr and an ambient dry bulb temperature of 74.6°F. For an insolation of 300 BTU/ft^2.hr a temperature of 210°F is reached with 40% collection efficiency. The maximum temperature of the air can be increased from 10 to 15°F with no loss in collector efficiency by allowing the air to flow over the absorbing surface and then back under the absorber (2 passes) instead of the standard single-pass configuration.[43]

Concentrator Systems

Concentrators offer several advantages for the heating of buildings:

1. Higher collection efficiencies result in smaller collectors
2. More compact heat storage
3. Year round collection of high temperature heat
4. More efficient operation of absorption cooling devices

Also, higher temperature heat collection makes the generation of electric power possible, with waste heat used for space heating and air conditioning.

When concentrators are used, water is no longer an acceptable heat transfer fluid so air or a commercial heat transfer fluid is used. At present, steering devices to keep concentrators oriented toward the sun are probably too expensive for home use. Steward[33] proposed a 962 ft^2 fixed cylindrical reflector to collect heat at 500°F. Russell's[34] fixed mirror concentrator has the additional advantage of remaining in sharp focus for all incident sun angles, permitting the efficient collection of heat at 500°F or more during most of the day. If air is used as the heat transfer medium, it can be circulated directly through a gravel tank for heat storage. Air is then brought from the gravel tank to the house, as required, for heating and other applications. Even more compact heat storage is possible with phase-change materials such as Glauber's salt (sodium sulfate decahydrate, Na_2SO_2-$10H_2O$). Telkes[44] has compared water, rocks and a typical phase-change material as follows:

Table 6. Thermal Storage of One Million BTU with 20°F Temperature Change

	Water	Rocks	Phase Change Material
Specific Heat (BTU/lb°F)	1.0	0.2	0.5
Heat of Fusion (BTU/lb)	-	-	100
Density (lb/ft^3)	62	140	100
Weight (lb)	50,000	250,000	10,000
Volume (ft^3) with 25% passage	1,000	2,150	125

Water can store heat over a range of temperatures approaching 200°F, and rocks can store heat (or coolness) at any conceivable temperature, but phase change materials melt and solidify at one temperature. Thus rocks and water can store heat in the winter and "coolness" in the summer, whereas two separate salt systems would be required to accomplish this. Phase change materials also cost more per BTU of heat storage than water or rocks. The great advantagesof the phase change material are, of course, considerably reduced weight and volume.

Roof Ponds

Perhaps the simplest technique for heating and cooling a house is to locate a pond of water 6 to 10 inches deep on the roof. The pond is covered by thermally insulating panels which can be open or closed. In the winter all the water is enclosed in polyethylene bags atop a black plastic liner. Sunlight heats the water to about 85°F during the day. At night, the insulating panels are lowered to prevent loss of the heat to space. During the summer, the insulating panels are open at night and closed during the day, so the water is cooled by radiation to space at night. Hay[45] reported the results of tests with a small 10 foot by 12 foot structure in Phoenix, Arizona, where temperatures were maintained close to 70°F year round by "pulling a rope twice a day"[20], even though ambient temperatures ranged from subfreezing to 115°F. A new two bedroom house[46] with a 10 inch roof pond is now under construction (Figure 14) in California at Atascadero near Paso Robles

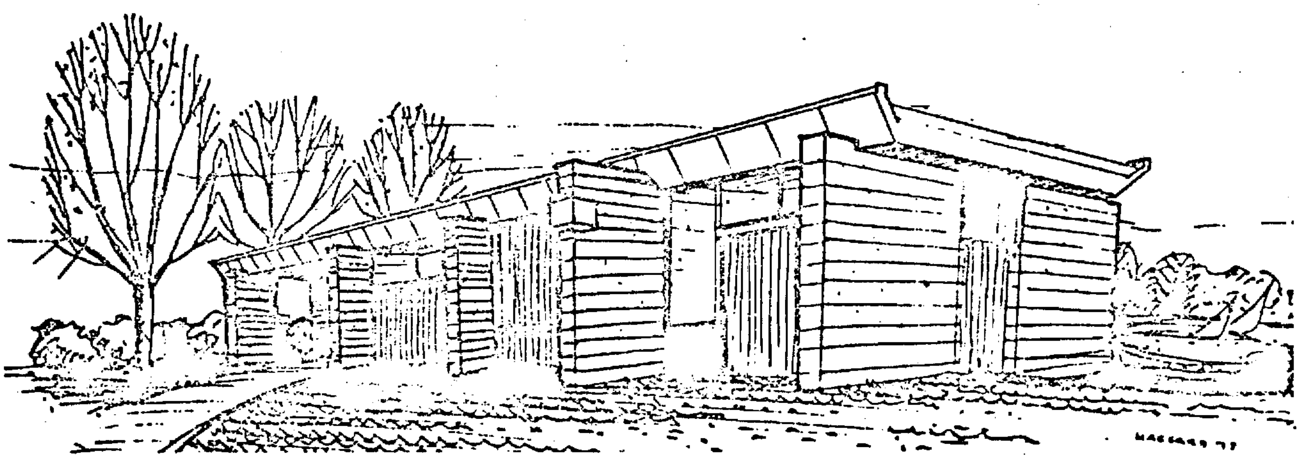


Figure 14. Solar Heated House with Roof Pond.[47]

which has recorded temperature extremes of 10°F and 117°F. This horizontal roof collector is not expected to meet the full heat demand because ambient air temperatures are lower, cloud cover is greater, and the location is two degrees more northerly than the Phoenix location of the test room. Summer cooling, however, should be better than at the Phoenix location. The roof pond is not visible at ground level. The house is to be occupied for one year while it is evaluated by professors from Cal. Poly University with financial support from HUD.[47]

SOLAR WATER HEATERS

Solar water heaters are currently in widespread use throughout many sunny areas of the world. A common arrangement is to have a flat plate solar collector on the roof which provides hot water by natural circulation to a tank located higher on the roof. The roof tank can be designed to look like a chimney. In Japan there are about 2 1/2 million solar water heaters of several different types currently in use [48]. The Japanese units employ a storage tank and collector as an integral unit, whereas in other countries the storage tank is usually separated[49]. The simplest and oldest type is a flat open tank on the roof, costing about $10 with a black bottom, which supplies water at 130°F in the summer and as high as 80°F in the winter. Since the water is sometimes contaminated by dust, a polyethelene film covering the tank can be added for a few dollars additional cost. The transparent cover lasts about three years, and increases the water temperature as well as preventing contamination. The standard heater size is about 3 feet wide, 6 feet long and 5 inches deep. These flat tank type water heaters are cheap, but suffer a major disadvantage in that they must be mounted horizontally, so they are not very effective in the winter when the sun is low. Closed pipe collectors can be mounted at a more optimum angle to the sun and thus provide hotter water during the winter months. The pipes are made of glass, plastic or stainless steel painted black mounted in a frame covered with glass or transparent polyethelyne plastic. The cost of these units range from $100 to $200. The purchasing of solar water heaters has declined since 1967 because of the availability of convenient and inexpensive heaters using fuels such as propane gas, however the recent rapid escalation of fuel prices will probably result in another increase in solar water heater sales.

In the United States about 60-70 square feet of collector can supply 75% of the water heating needs of apartments. One study which is underway is Project SAGE (Solar Assisted Gas Energy)[36] in southern California which is studying the technical and economic aspects of a solar assisted gas and electric water heating system for a typical Southern California apartment building. Figure 16 illustrates a solar-electric hot water system for an apartment complex, with a single collector and storage tank. This reduces the cost of collecting the solar heat for the apartment. The cost of the solar collection and storage is part of the cost of building and maintaining the apartment building, so it is included in the rent. The electric power consumption, however, is paid for by the individual user as part of his electric bill. This aspect of the system is attractive from the viewpoint of the apartment owner since it provides accountability for the consumption of hot water during periods when the solar input alone is not adaquate. The same general type of solar collector can be used to preheat water before it enters a conventional gas water heater. Water heating in a freezing climate requires that an intermediate heat transfer fluid (antifreeze solution) circulate through the collector in a closed loop and transfer its heat to water in a heat exchanger, as is shown in Figure 17. If the collector temperature is higher than the cold water inlet temperature (which is usually the case when the sun is shining on the collector), the pump is turned on and fluid from the collector circulates through a coil in the storage tank, thus preheating the water in the tank before it enters the conventional heaters. Solar heat is thereby used year round to reduce the consumption of gas or electricity for water heating. During parts of the summer all of the heat can be supplied by the solar collector. The water flowing through the collector can also be at a lower pressure than water in the storage tank.

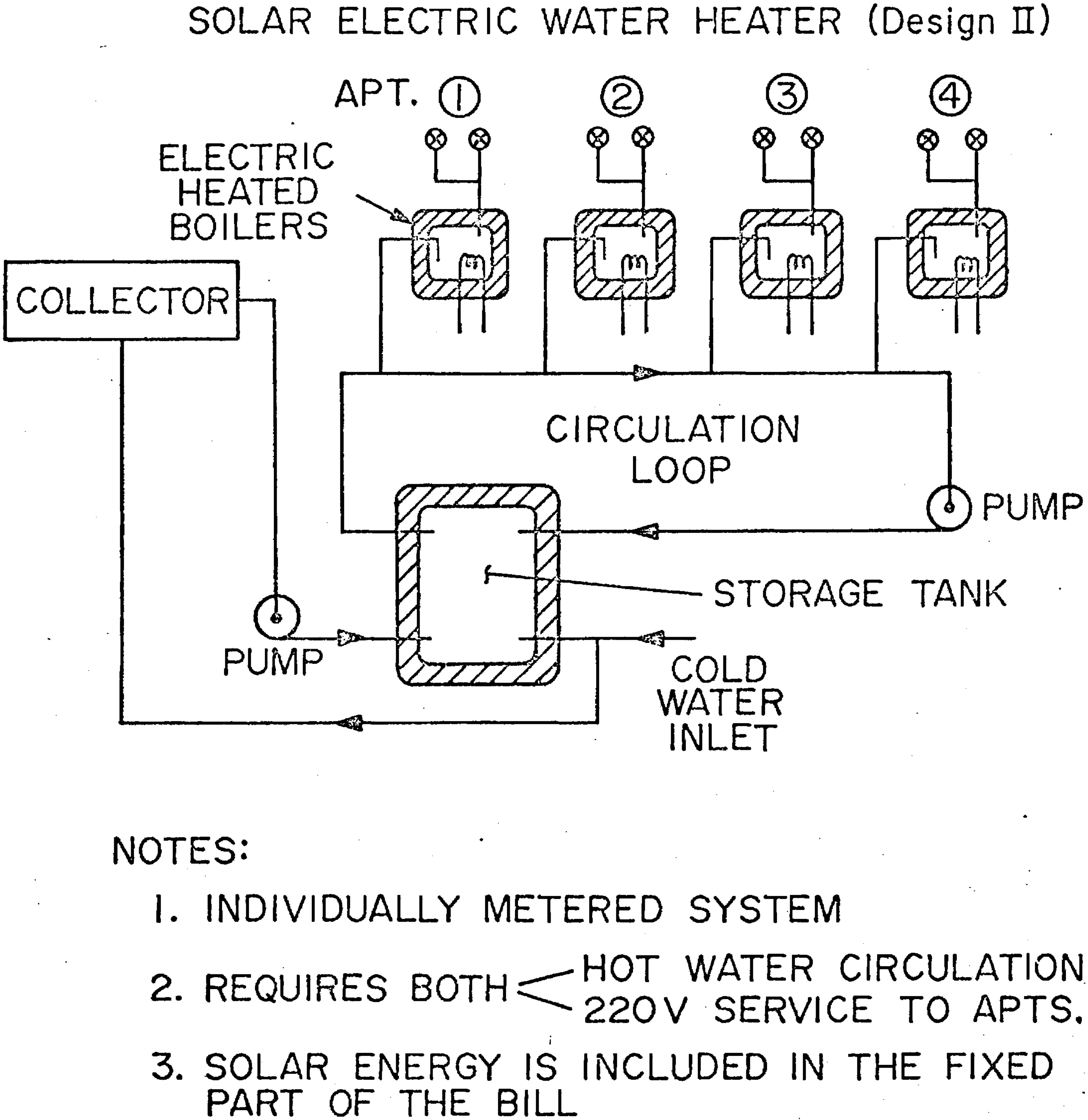


Figure 16. Solar-Electric Water Heater for Apartments[36]

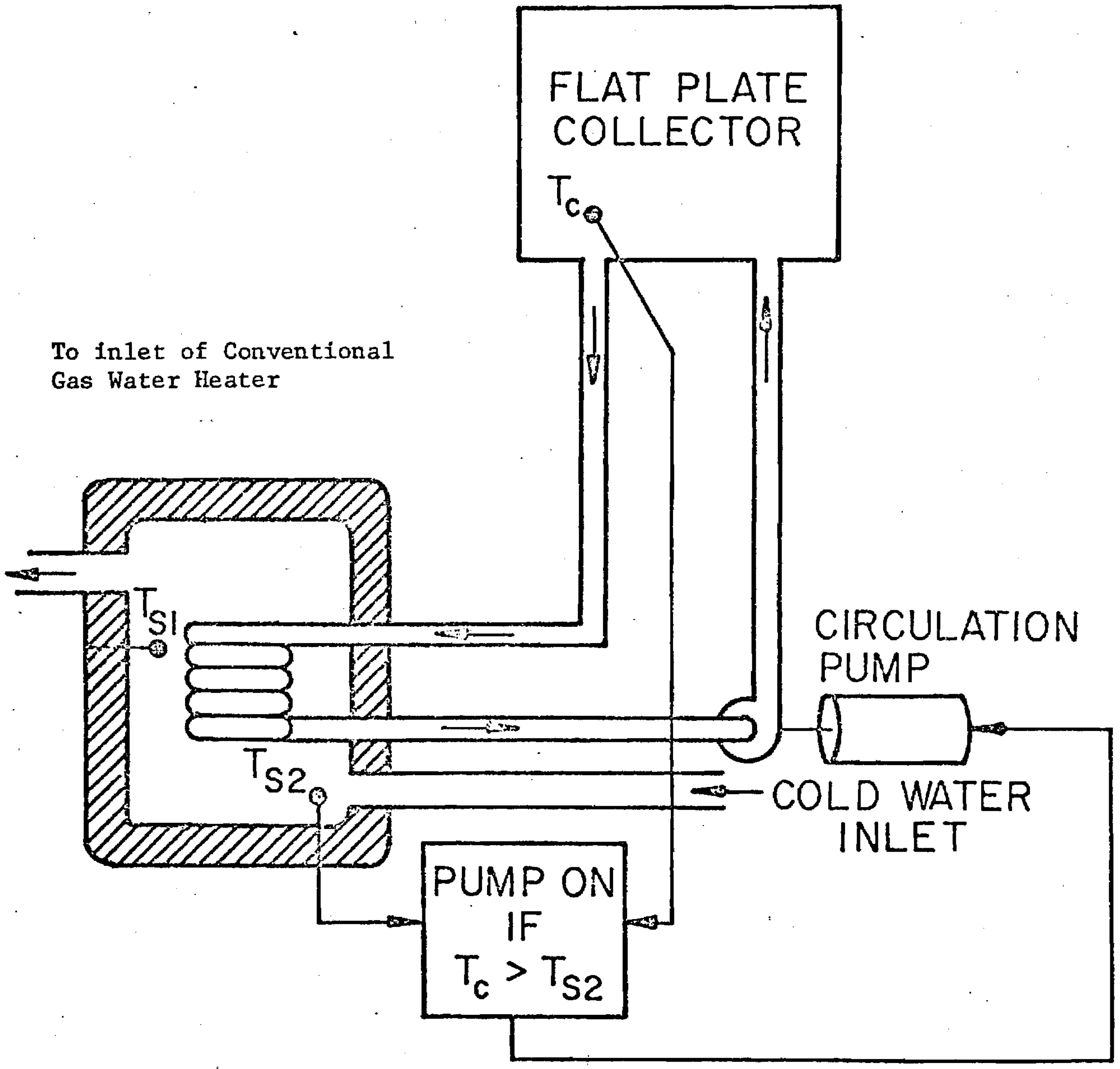


Figure 17. Solar-Gas Water Heater[36].

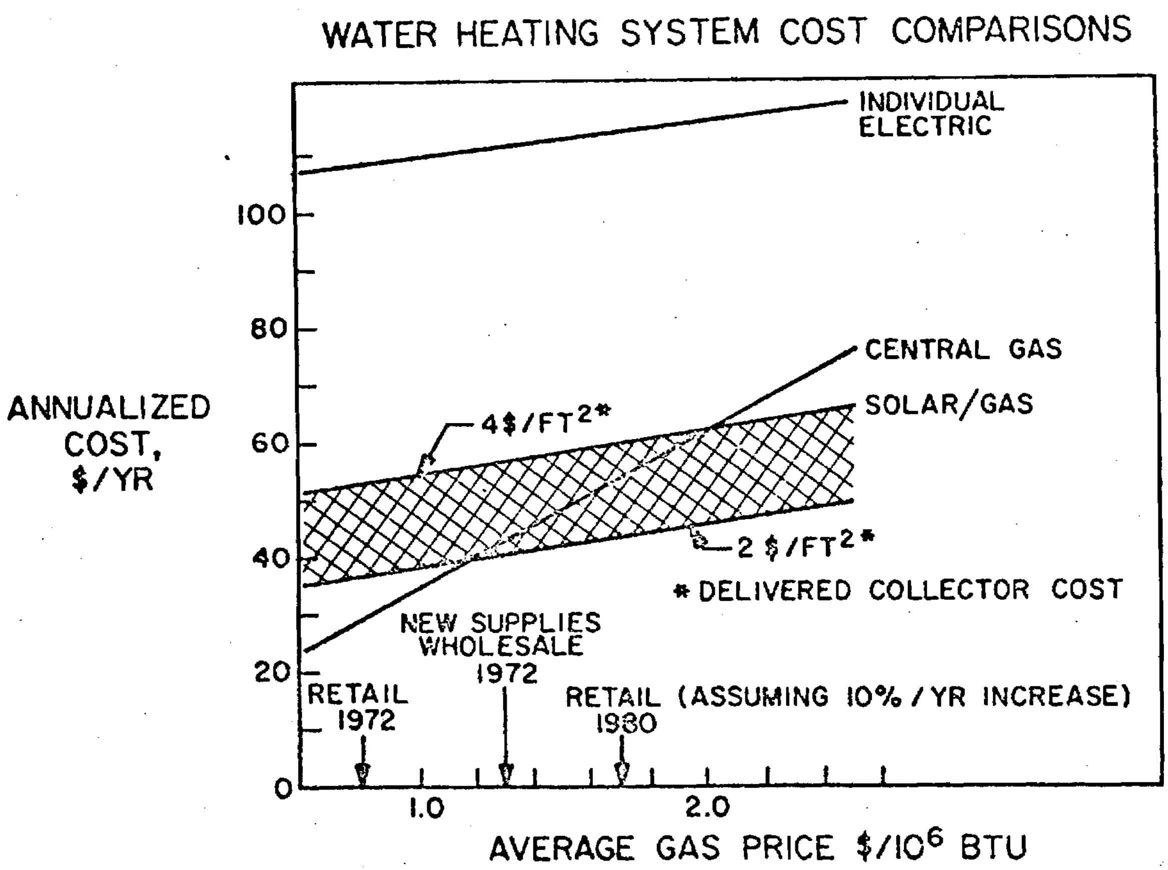


Figure 18. Water Heating Cost Comparisons.[36]

The costs of electric, gas, and solar-assisted gas water heating are compared in Figure 18. It is clear that as gas prices rise, and as solar collector costs decrease from the present $14/ft^2, solar-assisted gas water heaters will become cheaper than gas heaters alone. Already, solar assisted electric heating is cheaper than electric water heating alone, because of the high cost of electric water heating. At the present time gas is not being supplied to new units, because of short supply, in some areas of the country. The cost comparisons shown in figure 18 are based on a discount rate of 10%/year, a system life of 10 years, and an apartment size of 50 units[36].

Garg [50] has reported the design and performance of a large forced-circulation water heater of the same general configuration as that considered in the SAGE study. The flat plate collector consisted of 28 guage blackened aluminium sheet attached to 1.9 cm. diameter galvanized pipe with 10 cm

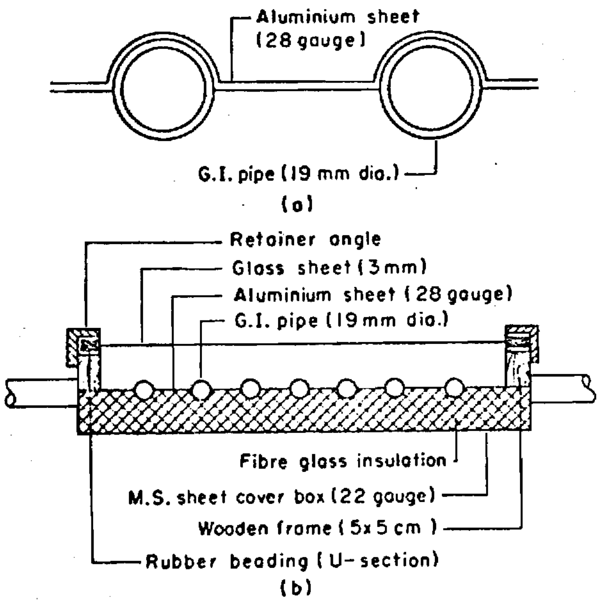


Figure 19. a) Flat Plate Collector, b) Collector Unit [50]

spacing, as shown in figure 19a. This collector configuration is optimized[51] for maximum heat collection per unit cost. A single 3 mm glass sheet covers the collector plate (Figure 19b). The design was based on work by Liv and Jordan[52] and earlier analytical work by Garg[53]. The vertical, cylindrical storage tank had a height of twice the diameter to reduce the heat loss when the hottest water is located in the upper part of the tank. The total collector area was about 100 ft^2, and heated the water in the tank to as hot as 130°F, with a collection efficiency of 50%. The pump consumed only 7 kilowatt hours per month. Gupta and Garg[54] have reported a detailed computer simulation of solar water heater performance.

Solar water heating has been quite popular in Israel, and by 1965 over 100,000 units had been installed.[55] One reason is that until recently the cost of electricity and heating fuels has been high enough to make solar heating more economical. The first solar water heaters in Israel were sold with a three-year guarantee. This was soon raised to 5 years, and for a small additional cost could be extended to 8 years.

Malik [56] reported the results of tests of ten types of collectors with

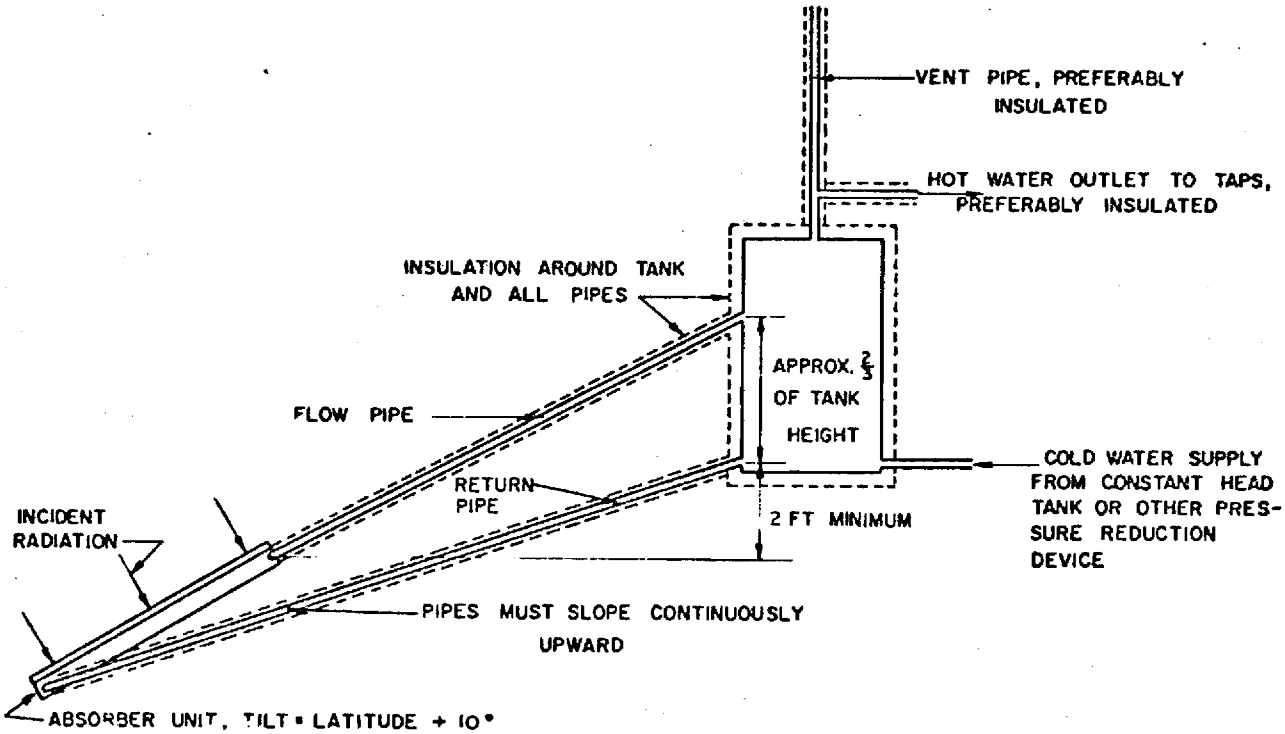


Figure 20. Natural Convection Solar Water Heater [56]

the natural convection water heater shown in figure 20. A small reverse flow occurs when the collector is cooler than the water in the tank, which has a certain advantage in the winter in that it prevents water from freezing in the collector. The tests measured the overall performance as affected by seasonal variations, type of transparent covering, insulation, height of storage tank and location of the point joining the flow pipe to the storage tank. The average efficiency was about 50% with a polyvinyl fluoride collector covering, and about 55% with glass. There was little effect on the efficiency of changes in insulation and seasonal variations.

In the United States today, solar water heating should probably be utilized with all new apartment and housing units in areas with mild winters.

In more northern climates where winter temperatures drop well below freezing, natural circulation systems such as shown in figure 20 and closed-loop systems such as indicated in figure 17 can be used. These systems now compete economically with alternative approaches, except in the northernmost parts of the country.

AIR CONDITIONING

Solar cooling is usually accomplished by using solar heat to operate a thermal absorption type refrigeration system. Daniels [57] described the basic principles of solar cooling as follows:

"The principles of absorption-desorption solar cooling are well established and fuel-operated refrigerators have long been on the market. In electrically operated refrigerators, a vapor such as ammonia is condensed to a liquid with a motor-driven pump, and the heat evolved is removed with circulating air or water at room temperature. The liquid is then vaporized in an insulated box and heat is removed by the vaporization to give the cooling effect. In solar refrigeration, the cycle is similar except that the pressure is built up by heating a concentrated solution of ammonia to give a high vapor pressure, instead of compressing the vapor mechanically. There are two connecting, gas-tight vessels, one of which contains liquid ammonia and the other a very concentrated solution of salt in liquid ammonia. The salt solution has a much lower vapor pressure, and the liquid ammonia vaporizes in its compartment, thereby cooling it, and dissolves in the salt solution contained in the other compartment. The system is regenerated by using focused solar radiation to raise the temperature of the salt solution to such a high temperature that the vapor pressure of ammonia in the solution exceeds the vapor pressure of the pure liquid ammonia in the second compartment. In this way, the operating cycle produces cooling by evaporating ammonia as it goes into the concentrated solution of salt, making it more dilute; and the solar regeneration drives out the ammonia from the diluted salt solution to produce pure ammonia and leaves a more concentrated solution.

A cycle has been studied in which a concentrated solution of lithium bromide absorbs water vapor and causes liquid water in another compartment to vaporize and produce a cooling effect. The lithium bromide solution is concentrated again by heating the diluted solution with solar radiation and the system is operated on a continuous basis. A laboratory was partly air conditioned by the sun for a while during these tests."

A continuously operating absorption air-conditioning system was built and tested in the early 1960's at the University of Florida [58]. Hot water was used to heat a high-concentration, ammonia-water solution (50 to 60% ammonia by weight) in a generator, driving the ammonia out of the solution. The ammonia vapor was then condensed and expanded through an adjustable expansion valve and entered the evaporator as a two-phase mixture. The liquid component evaporated, cooling the water circulating through tubes in the evaporator, and then reabsorbed into the water, and the ammonia solution was pumped back to the generator to repeat the cycle. Ten 4 foot by 10 foot flat-plate solar collectors provided the hot water to operate the air conditioner. The absorbing surfaces were tubed copper sheets painted flat black, placed in galvanized sheet-metal boxes with two inches of foam-glass insulation behind, and a single glass cover. The system was operated with heating water temperatures ranging from 140 to 212°F. The maximum cooling effect was 3.7 tons, and steady operation was achieved with 2.4 tons of cooling.

Teagen [59] proposed a solar powered air conditioning unit driven by an organic Rankine cycle engine. Solar heat would be used to vaporize an organic fluid at a temperature between 160°F and 280°F to drive a Rankine cycle engine, which in turn drives the compressor of a vapor-compression air conditioning system. The coefficient of performance should compare favorably with absorption air conditioning systems, but at the present time none have been built.

Lof [60] compared the cost of solar heating, solar cooling, combined solar heating and cooling, oil or gas heating and cooling, and electric heating and cooling (Table 7) and concluded that, except for the northern-most part of the country, combined solar heating and cooling is cheaper than solar heating or cooling alone. Solar costs were based on $\$2/ft^2$ collectors, amortization over a 20 year life, 8% interest, 1970 prices, and an additional $1,000 capital cost for solar air conditioning over electric, gas or oil air conditioning. Water heating was included, and the water storage cost was taken to be $0.05/ lb water.

Table 7. Heating and Cooling Costs [60]

$ Per Million BTU

	Oil or Gas	Electric	Solar Heating	Solar Cooling	Solar Combined
Albuquerque	0.95	4.63	2.01	3.24	1.70
Miami	2.04	4.87	11.63	2.19	2.07
Charleston	1.03	4.22	3.34	3.50	2.47
Phoenix	0.85	5.07	2.86	2.05	1.71
Omaha	1.12	3.25	2.93	5.41	2.48
Boston	1.85	5.25	3.02	8.74	3.07
Santa Maria	1.52	4.28	1.57	14.60	2.45
Seattle	1.96	2.29	3.15	19.63	3.79

As is seen from Table 7, solar heating is very costly in Miami where not much heat is needed, and likewise solar air conditioning is not economical in northern climates where little air conditioning is needed. The primary reason that the combined system is usually cheaper than either alone is that it permits both summer and winter utilization of the solar collector, which is the most expensive part of the system. Thus, in most parts of the U.S., the economics favor combined solar heating and cooling, rather then either alone. Figure 21 illustrates such a combined system using a common collector, storage tank, auxiliary heater, and blower for both heating and air conditioning.

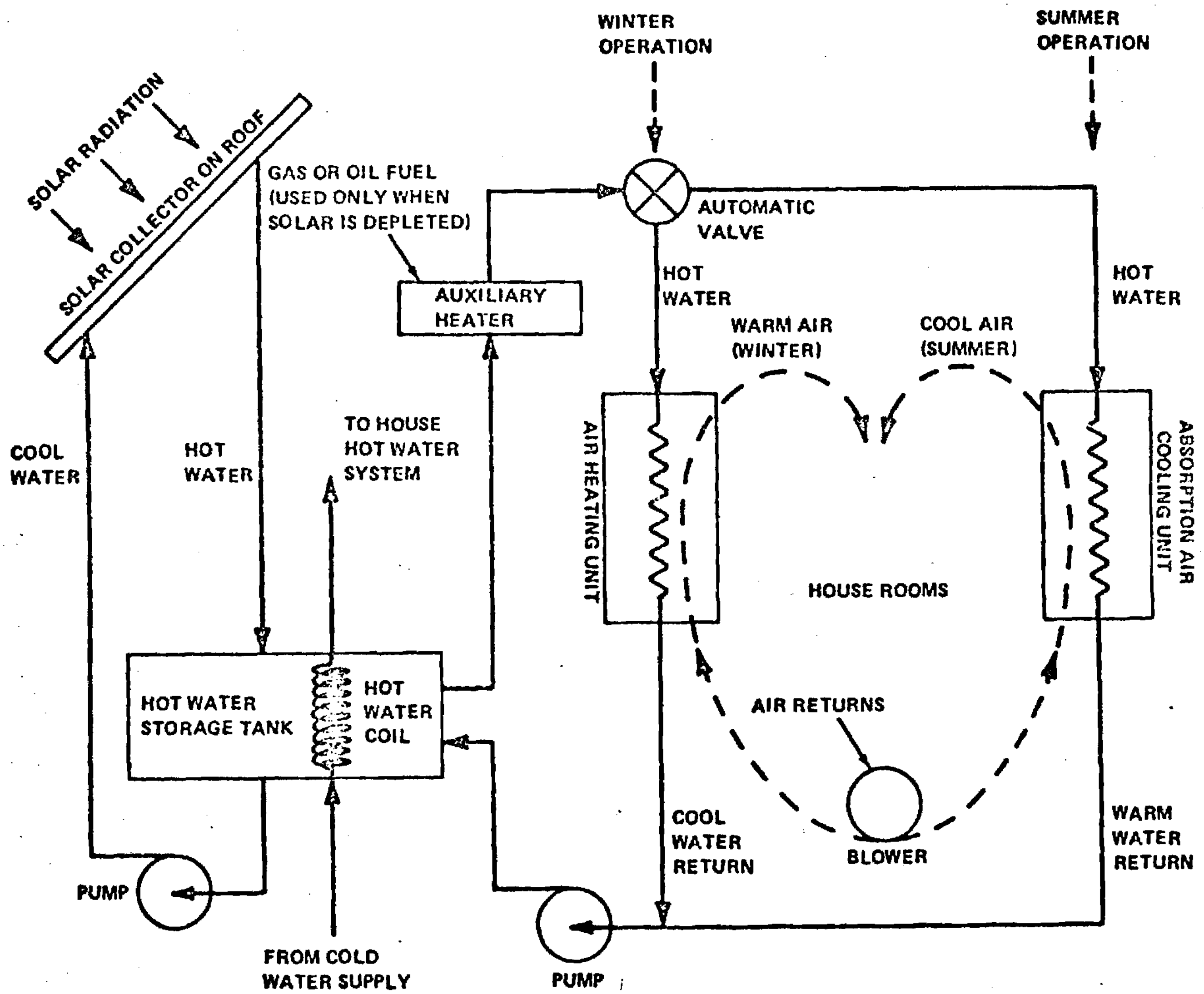


Figure 21. Combined Solar Heating and Cooling System.

ELECTRIC POWER GENERATION

A variety of approaches have been used for converting solar energy into electricity, including solar-thermal conversion, photovoltaic devices, and bio-conversion. Sunlight is an abundant, clean source of power, all that is required is the development of technology to economically convert this energy into electricity.

The NSF/NASA Solar Energy Panel [13] has identified the various possible steps leading from solar radiation to power delivered to the consumer (Figure 22). In this scheme plants, rivers, winds, ocean currents and ocean temperature gradiants are considered natural collectors of solar energy. Solar energy can also be collected directly as heat, or converted into electricity via the photoelectric effect. If collected as heat, the heat can be stored for use when the sun is not shining. The heat can be used to operate a power plant or to produce a chemical fuel, such as through the thermochemical production of hydrogen. The fuel can be stored, and used as needed to produce electric power, such as with the hydrogen-air fuel cell.

With so many possible approaches available for the production of electric power, the problem then is to choose that approach which is most cost-effective for a specific application. This is sometimes difficult since technology is advancing rapidly in most of these areas, and the comparative economics becomes uncertain. At present, the two technological approaches which offer the most promise are photovoltaic conversion with electrical storage, and solar-thermal conversion with heat storage for nighttime operation.

Solar-Thermal Power Generation

The two main approaches to solar-thermal power generation are the solar furnace approach, in which sunlight reflected from many differant locations is concentrated on a single heat exchanger, and the solar foam, with large numbers of linear reflectors focusing solar radiation on long pipes which collect the

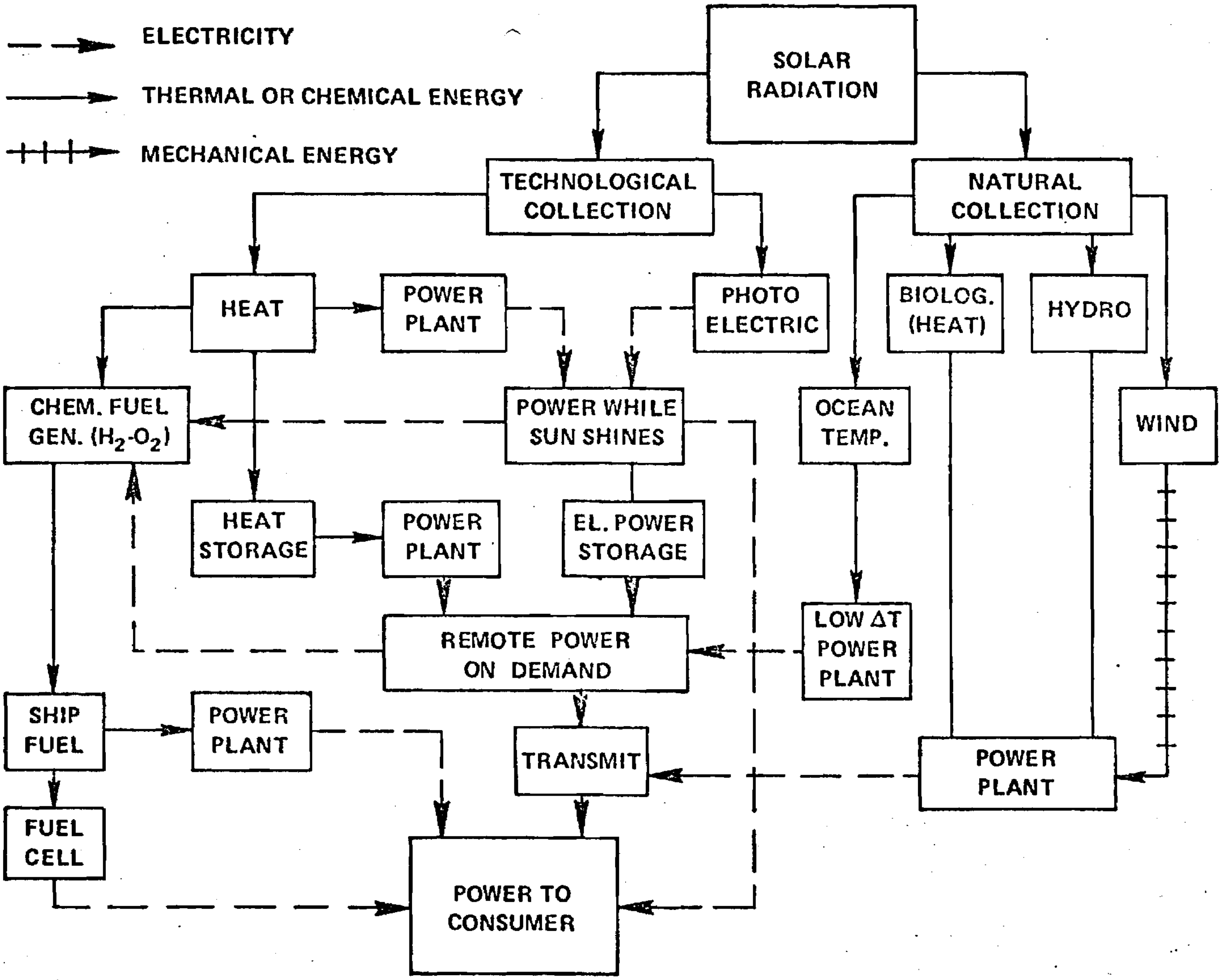


Figure 22. Possible Approaches for the Conversion of Sunlight into Electricity.[13]

heat.

The tower concept (Figure 23) proposed by Lenitske[61] in 1949 is a good example of the solar furnace approach. A large number of flat mirrors covering a large area of land independently focus sunlight onto a boiler, which is mounted at the top of a tower located near the center of the field of mirrors to produce high temperature steam for driving a turbine. A 50 kilowatt plant

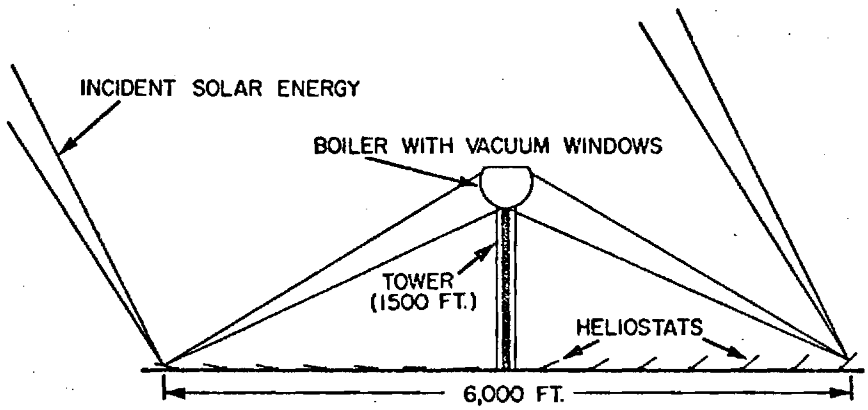


Figure 23. Tower Concept for Power Generation

has been built and operated in Italy [62]. An advantage of this system is that the separate mirrors and steering mechanisms can be inexpensively mass produced, and the smaller reflectors are less subject to high wind loadings than a single large steerable concentrator of the same total collector area.

A recent proposal by Hildebrant and Vant-Hull [63] involves using over a thousand 10 foot square mirrors covering a 6000 foot diameter circle of about one square mile area to reflect sunlight onto the boiler on top of a 1500-foot high tower (Figure 23). Each mirror would be steered separately by a heliostat as shown in figure 24. Hildebrant acknowledges that "Since the major expense of solar energy collection employing a solar furnace would be the heliostats, considerable research needs to be done in order to develop a heliostat which could be economically mass produced." The 150 foot diameter, 1500 foot high tower would cost about $15 million. The boiler could be made of steel and operate in the 1000°C range, and the solar image size at the boiler would be 31 feet in diameter. The outer boiler surface would be black and surrounded by an evacuated glass envelope. About 20% of the incident solar energy would be lost upon reflection by the mirrors, and another 6% lost by reflection from the boiler glass envelope. If 45% of the land area is covered with mirrors the boiler could collect 630 BTU/day per square foot of mirrors in the Southwest U.S. in the winter,

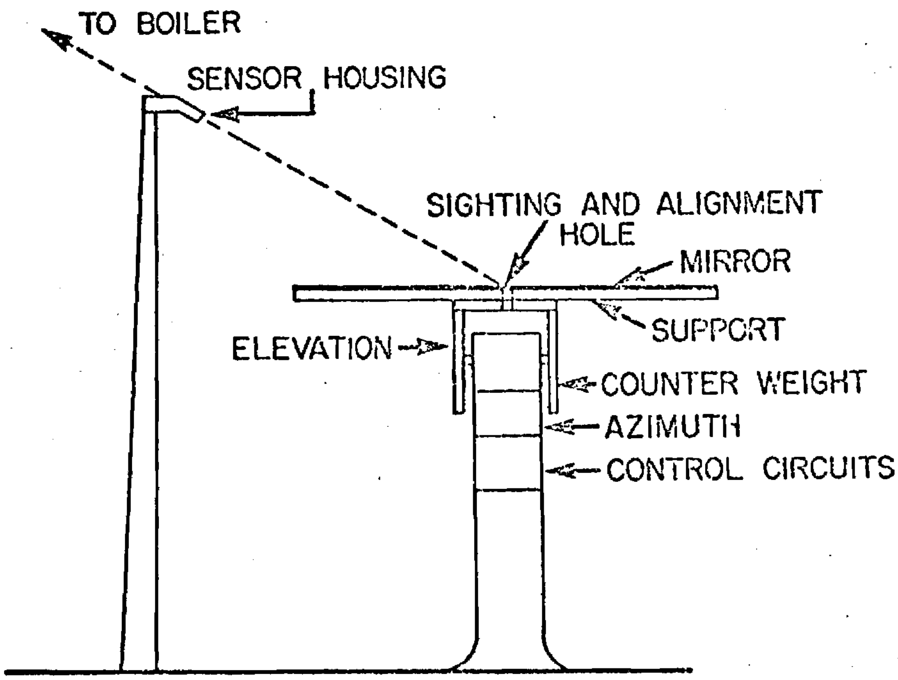


Figure 24. Heliostat System for Steering Mirrors

1320 BTU/ft^2 day in the spring and fall, and 1620 BTU/ft^2 day in the summer. The total cost of heat collected by this plant is estimated at \$0.48 per MBTU [63], which is compet itive with the cost of fossil fuels delivered in large quantities to a power plant. This cost estimate is based on a \$2/ft^2 cost for the mirrors and heliostats and \$15 million for the tower. The heliostats must aim the mirror with an accuracy of 0.2° in the presence of winds.

Trombe [64] has developed a megawatt solar furnace in France employing heliostats with 20 inch square flat glass mirrors and a fixed parabolic concentrator on the side of a nine-story building. The flat mirrors reflect sunlight toward the fixed parabolic concentrator, which focuses the sunlight. The heliostats and mirrors cost \$21/ft^2. Walton [65] is preparing to use this facility for tests of boiler surfaces which might be used with the tower concept for electrical power generation. Major problem areas which must be investigated are 1) heat shock from the many thermal cycles which result from clouds passing in front of the sun and 2) investigation of the absorption - reflection - radiation characteristics of potential boiler surfaces operating at high temperatures and high heat fluxes.

"Solar foams" have been proposed using parabolic trough concentrators to focus sunlight onto a central pipe surrounded by an evacuated quartz envelope (Figure 6). Heat collected by a fluid flowing through the pipes could be stored at temperatures over 1000°F in a molten eutectic , [66] and used as required to produce high enthalpy steam for electric power generation. Another approach is to store the heat in rocks, and extract the heat as required to generate steam on demand (Figure 25).

Russell [67] has proposed a central station electric power plant based on his fixed-mirror solar concentrator which produces a sharply focused line image regardless of the incident sun direction. The major advantage of the fixed mirror concentrator is its potential cost reduction as compared with other types of concentrators capable of providing heat at more than 1000°F.

In order for large scale solar-thermal electric power generation to become economically feasible, the cost of the collector must not exceed about one dollar per square foot [68]. However, concentrating solar collectors which must be steered to follow the sun cost more than \$4/ft^2, and a major part of this cost is the steering mechanism and the mechanical structure which must withstand reasonable wind loadings. The fixed mirror concentrator, on the other hand, does not have to be steered and need not be self-supporting, so fabrication of these concentrators should be much cheaper then steerable reflectors. Since the point of focus always lies on the reference cylindrical surface, the heat exchanger pipe can be supported on arms that pivot at the center of the reference cylinder. This greatly simplifies the positioning of the heat exchanger.

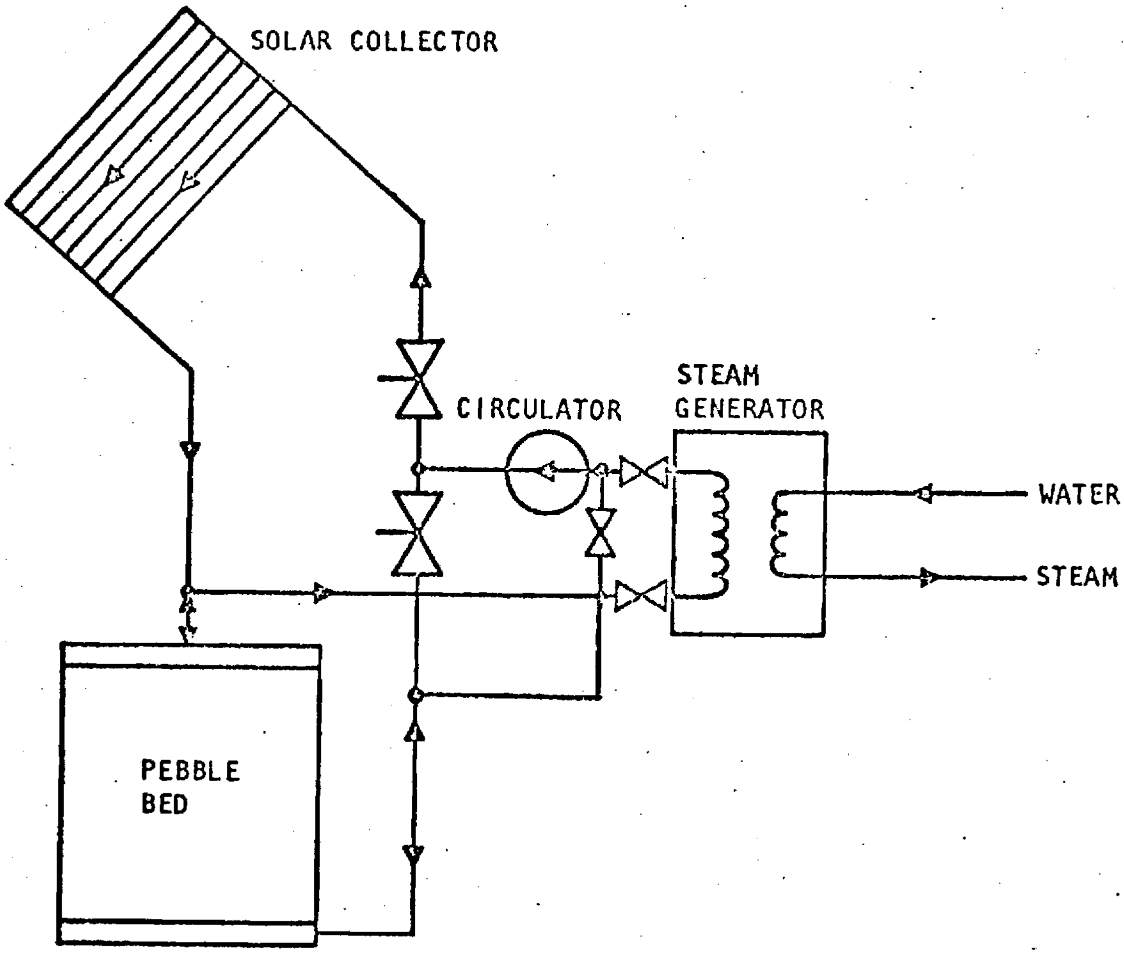


Figure 25. Flow Diagram for a Solar Thermal Power Plant [67]

Russell's proposed power plant for the Southern California desert would be arranged in modules (Figure 26) with 30 foot wide mirrors arranged in a 1500 by 1880 foot array, with a gravel tank for heat storage and the steam generator located in the center. Air at 100 psi is heated in the collecting pipes by the focused sunlight and flows through the pebble bed and/or the steam generator. Steam at 1000°F could be supplied from 9 of these modules to a centrally located turbogenerator of 162 MWe capacity. Figure 27 illustrates the fixed mirror concentrator array. Costs of power from this facility

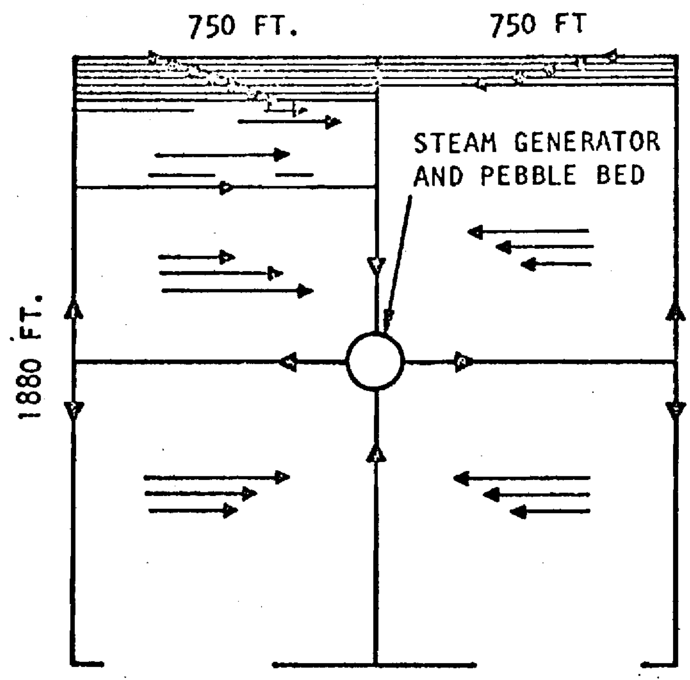


Figure 26. Module Of fixed MirrorPower Plant[67]

is estimated to be competative with alternative means of power generation. Land costs would be negligible since, even at $1000/acre, the land cost is only $0.023/ft^2$. Desert land is even cheaper.

Meinel[69] has proposed a 1,000,000 MWe solar-thermal power plant covering about 13,000 square miles of desert extending from the upper regions of the Gulf of California as far north as Nevada (Figure 28). The plant would use waste heat to produce 50 billion gallons of water each day, enough to meet the needs of 120,000,000 people. The proposed plant would use a circulating liquid metal (sodium or NaK) to extract heat from a solar foam and store it in a phase-change salt or eutectic mixture at temperatures in excess of 1000°F. Power would be produced by a high pressure steam turbine-generator, and the low pressure steam from the turbine used to distill water. The total cost of solar heat collected by this plant is estimated at $0.50 per KW hour.

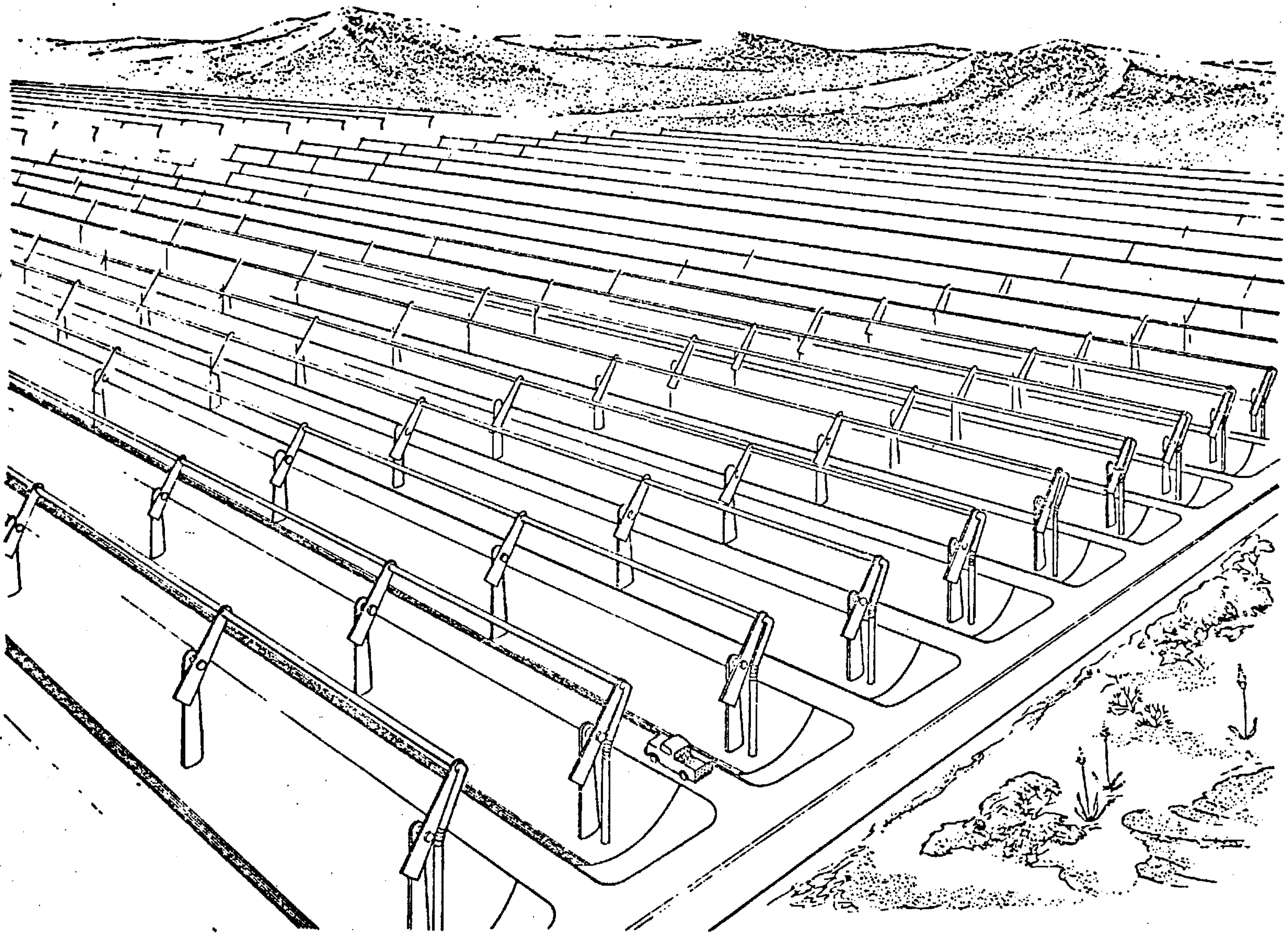


Figure 27. Artist's concept of fixed-mirror solar concentrators showing the mirrors and the tracking heat absorber pipes [67]

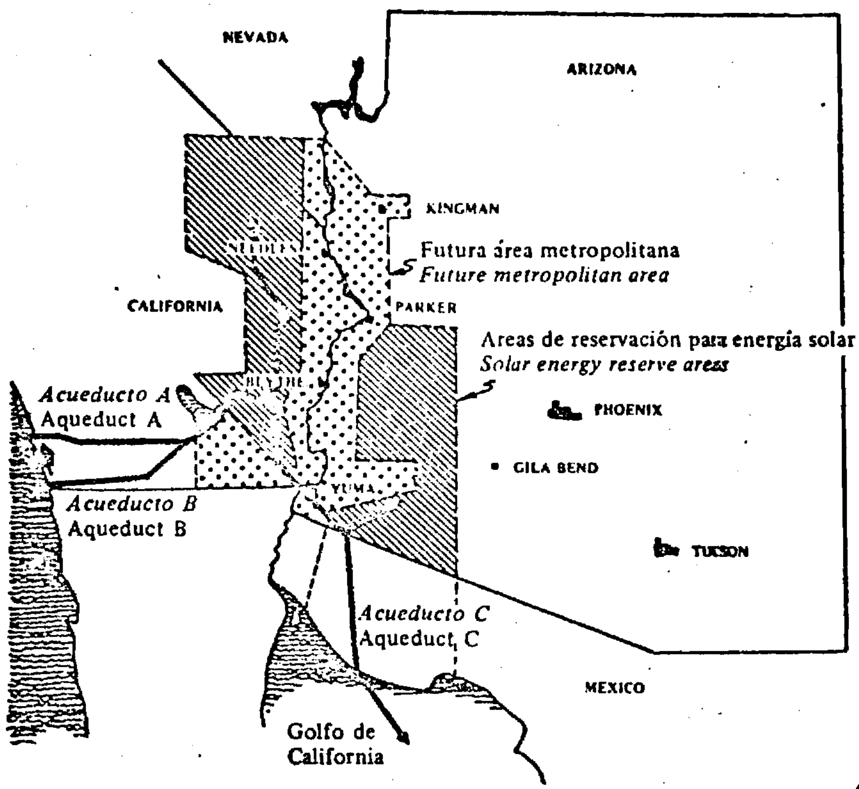


Figure 28. Proposed Location of National Solar Energy Reserve[69]

Photovoltaic Power Generation

Solar cells offer a potentially attractive means for the direct conversion of sunlight into electricity with high reliability and low maintainence as compared with solar-thermal systems. The disadvantages at present are the high cost of about \$25/watt [70] and the difficulty of storing large amounts of electricity for later use as compared with the relative ease of storing heat for later use. The cost of solar cells is expected to be considerably reduced when cells are manufactured in large quantities using new production techniques for obtaining ribbons or sheets of single crystal silicon. At present large crystals of silicon or other semiconducting material are grown and then sliced into thin cells; new techniques for producing the thin slices directly use edge defined film growth [71], dendritic growth [72], rolled silicon [73], or sheets of cast silicon which are recrystallized through heated or molten zones [74]. Silicon itself is very cheap since it is the second most abundent element in the earth's crust, and is produced in the U.S. at an annual rate of 66,000 tons at a cost of

$600/ton, so when the most suitable of these mass manufacturing techniques is utilized the cost of solar cell arrays should be reduced to $1/watt or less, making them useful for the large scale generation of electric power [71, 75].

Four companies which manufacture solar cells are Heliotech, Centralab, Solar Power Corporation (Exxon), and Sharp. Solar Power Corporation [76] sells a small solar power module that produces 1.5 watts at a solar intensity of 100 mW/cm^2. The current and power output characteristics of these solar cells (typical of solar cells in general) are given by figure 29. Standard conditions are 0°C and 1000 W/m^2 insolation, typical conditions are 25°C and 800 W/m^2

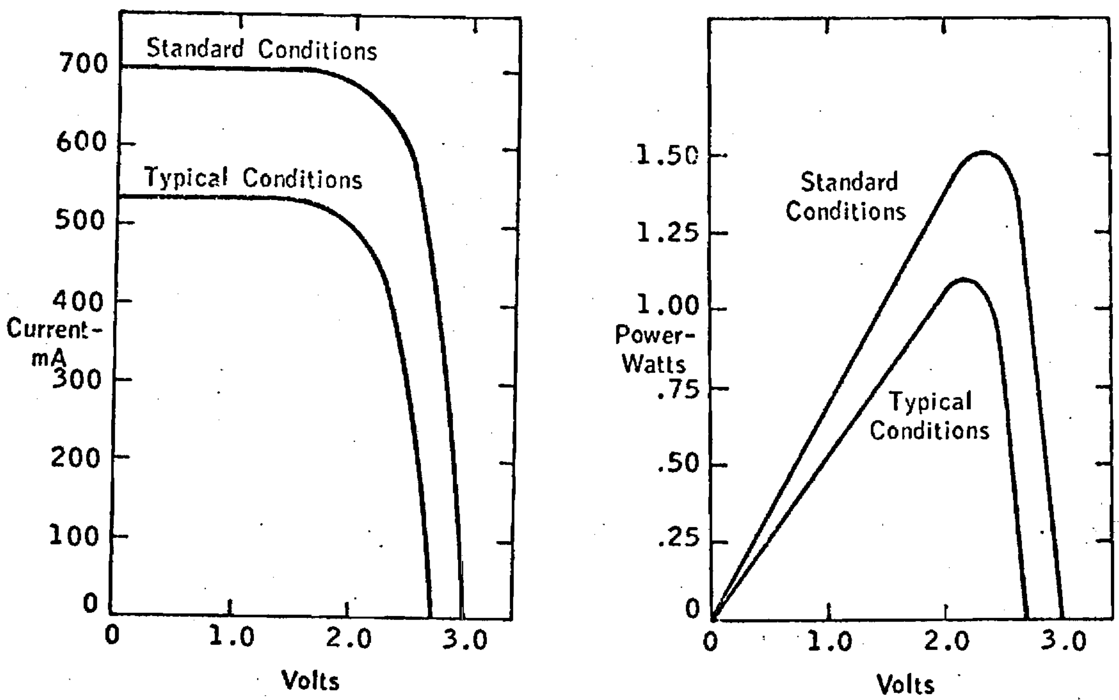


Fig. 29. Operating Parameters of Solar Cells[76]

are 0°C and 1000 W/m^2 insolation, typical conditions are 25°C and 800 W/m^2

insolation. The solar array module consists of five 2.17 inch diameter silicon solar cells attached to a 13 1/2 inch by 2.9 inch panel and is usually used to change storage batteries to provide a continuous supply of power in remote locations. Tests in Arizona showed no degradation in output over a six month period. One power system being used at present to power navigational lights consists of 80 of these modules, 28 100 amp-hr 12 volt storage batteries, and the electronic control circuit. This power supply is cheaper to use than the alternatives; the Coast Guard saves about $3 million per year by using solar powered buoys [77]. The cost reduction is mainly due to the smaller number of trips out to the buoys for servicing. Wires are used to keep seagulls off, but nothing is done about snow. NASA's experience testing solar cell arrays in Cleveland has shown no significant reduction in power due to dirt or dust accumulation and little problem with snow [20].

Rink and Hewitt [78] have studied the possibility of using a large solar cell array to supply the electric power needs of the western United States in 1990, assuming that solar cells can be mass produced at $1/watt. An array covering 192 square miles, coupled with pumped storage, would supply the 14,300 MWe needed by Arizona in 1990 for about $58 billion and an array covering 2200 square miles (44 miles by 50 miles) would supply 40% of the electrical power needs of the eleven western states for a capital cost of around $673 billion. Since these costs are far in excess of alternative means of power generation, it appears that even at $1/watt solar cells will be too expensive for central station power generation. Wolf [79] has concluded that the cost of solar cells must be reduced to about $0.20 per watt before solar cell arrays become practical for central station power generation.

The cost of generating electric power with solar cells can be reduced by using concentrators to focus sunlight onto the cell. One simple type of concentrator is the reflecting cone [26, 80] (Figure 30). Without external cooling concentration ratios of up to five can be used without seriously reducing the

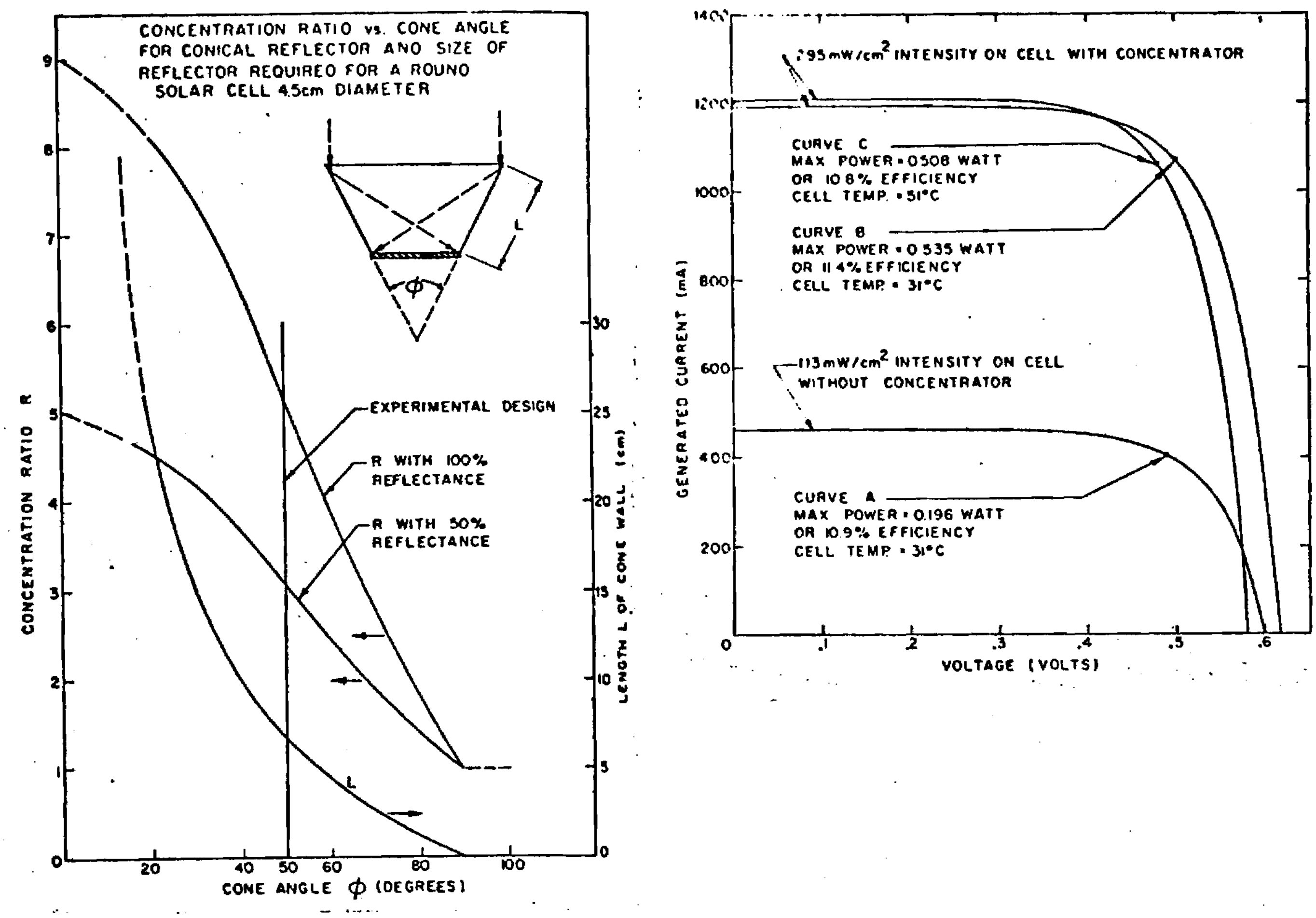


Figure 30. Concentration Ratio of Cone Reflector and Effect on Solar Cell Performance

cell performance due to cell heating. Higher concentration ratios are possible with external cooling. Solar cell arrays with concentrators must be steered to follow the sun ; in the case of the conical concentrator tested by Ralph [80] the output is reduced below that with no concentrator if the angle of incidence is less than 60 degrees, and at angles of less than 45 degrees the output is negligible.

Another related design is the channel concentrator consisting of two flat reflecting surfaces at an angle of 30^{o} placed on both sides of a line of solar cells. The theoretical maximum concentration ratio is 3; an actual concentration ratio of 2.25 was achieved with a channel concentrator array built by Ralph[70]. His array used 2 in by 2 in silicon solar cells at the base of the V channel. Five channels with 30 cells each formed a 4.75 lb., 1 foot by 2 foot array producing 12 watts at 12 volts.

With external cooling, silicon solar cell outputs can be increased by more than 100 with concentrating systems [81]. Using experimental data[82] for cells operating with solar fluxes between 14 and 28 watts/cm^2, Beckman[83], et.al., designed a system to produce 50 watts of electrical power from 36 square centimeters of cell area by using a 5 1/2 foot parabolic concentrator to provide a solar flux of 28 watts/cm^2. The cells would be water cooled to maintain their temperature at 200^{o}F. Five watts would be required to pump the water. Lidorenko[30], et.al., built and tested a 250 watt electric power plant using a concentrator consisting of 26 plane mirror facets forming an approximate parabolic cylinder. The concentrator increased the power output a factor of 5.2 over the power output with no concentrator, the solar cells were water cooled, and the overall plant efficiency was 2.7%[84]. Another plant was developed by the same group using channel concentrators with a concentration ratio of 2.5, and not requiring water cooling. These plants were developed "to provide power for water pumps in the grazing areas of the southern regions of the U.S.S.R.". According to <u>Moscow News</u>[85], one of their solar cell plants "has been installed at the Bakharden state livestock-breeding farm situated in the Kara-Kum Desert, Turkmenia. Its output equals about 400 watts-enough to lift from a depth of 20 meters, a sufficient amount of water to water 2,000 sheep".

TOTAL ENERGY SYSTEMS

The feasibility of using solar energy to provide for all of the various energy needs of a home, business, or community requires either the development of inexpensive solar cells or an economical means of collecting solar heat at high temperatures and converting it to electric power. Photovoltaic cells can be combined with a flat plate collector (Figure 5) so that the radiant energy not converted into electric power is collected as heat and used to supply hot water, space heating, absorption refrigeration, and air conditioning. Figure 31 illustrates a solar cell flat plate collector which would permit utilization of up to 60% of the available solar energy. Collectors such as this mounted on vertical walls and/or part of the roof of a house or apartment building can supply all the various types of energy needs of the building. Figure 32 is a schematic showing the energy flows for a residential solar energy system using solar cell flat plate collectors. This type of system is perhaps the ultimate in residential solar energy utilization, since both heat and electric power are produced without any moving parts, except for the pump or blower circulating coolant through the collector.

Advantages of this type of solar electric-thermal total energy system were listed by the NSF/NASA Solar Energy Panel[13] as 1) the collector uses the same land area as occupied by the building, and thus there is minimal effect on the environment through use of land presently being used for other purposes. 2) About three times the present average household consumption of eletric power can be collected from average-size family residences, even in the

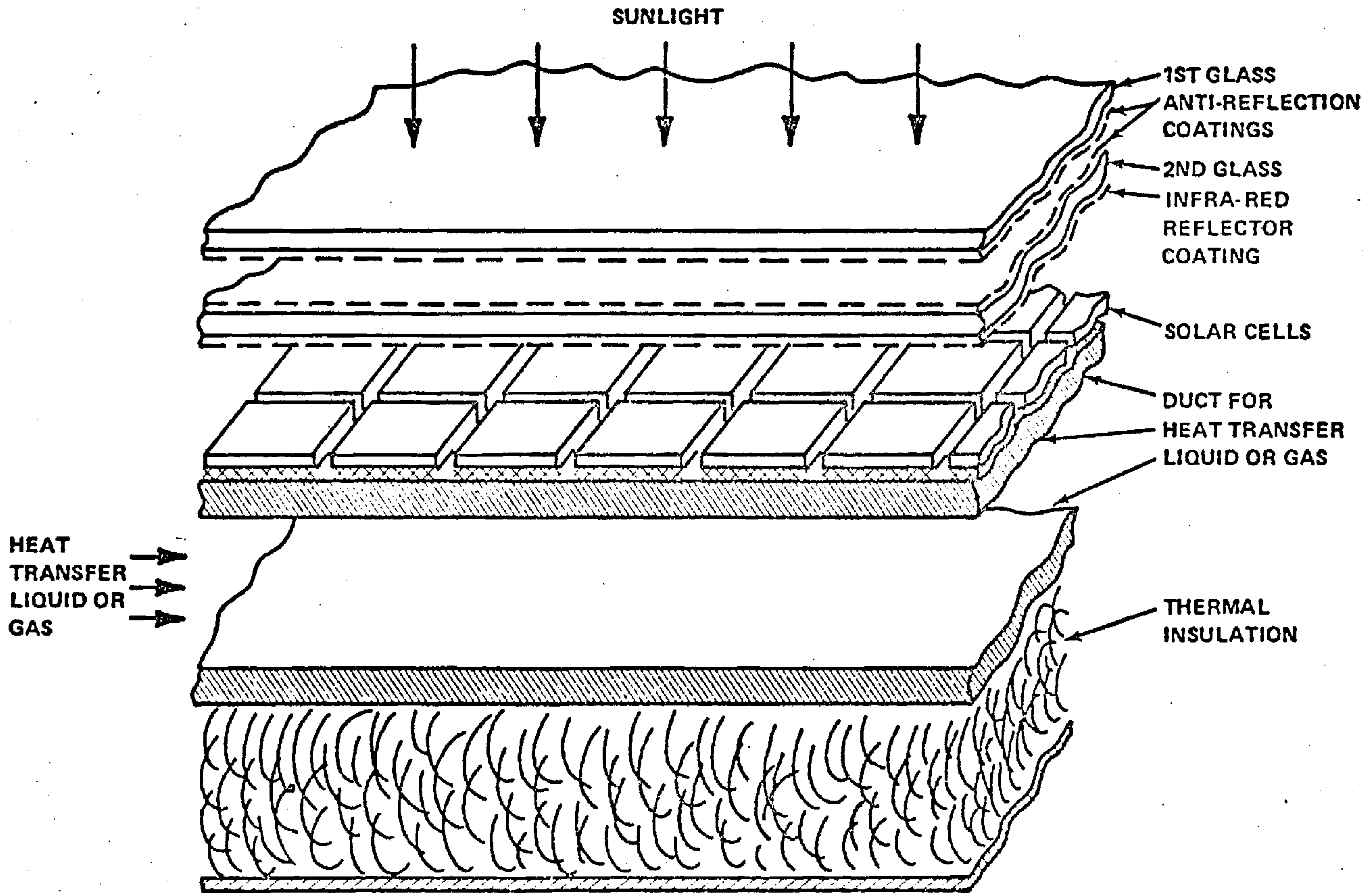


Figure 31. Flat Plate Collector with Solar Cells[13]

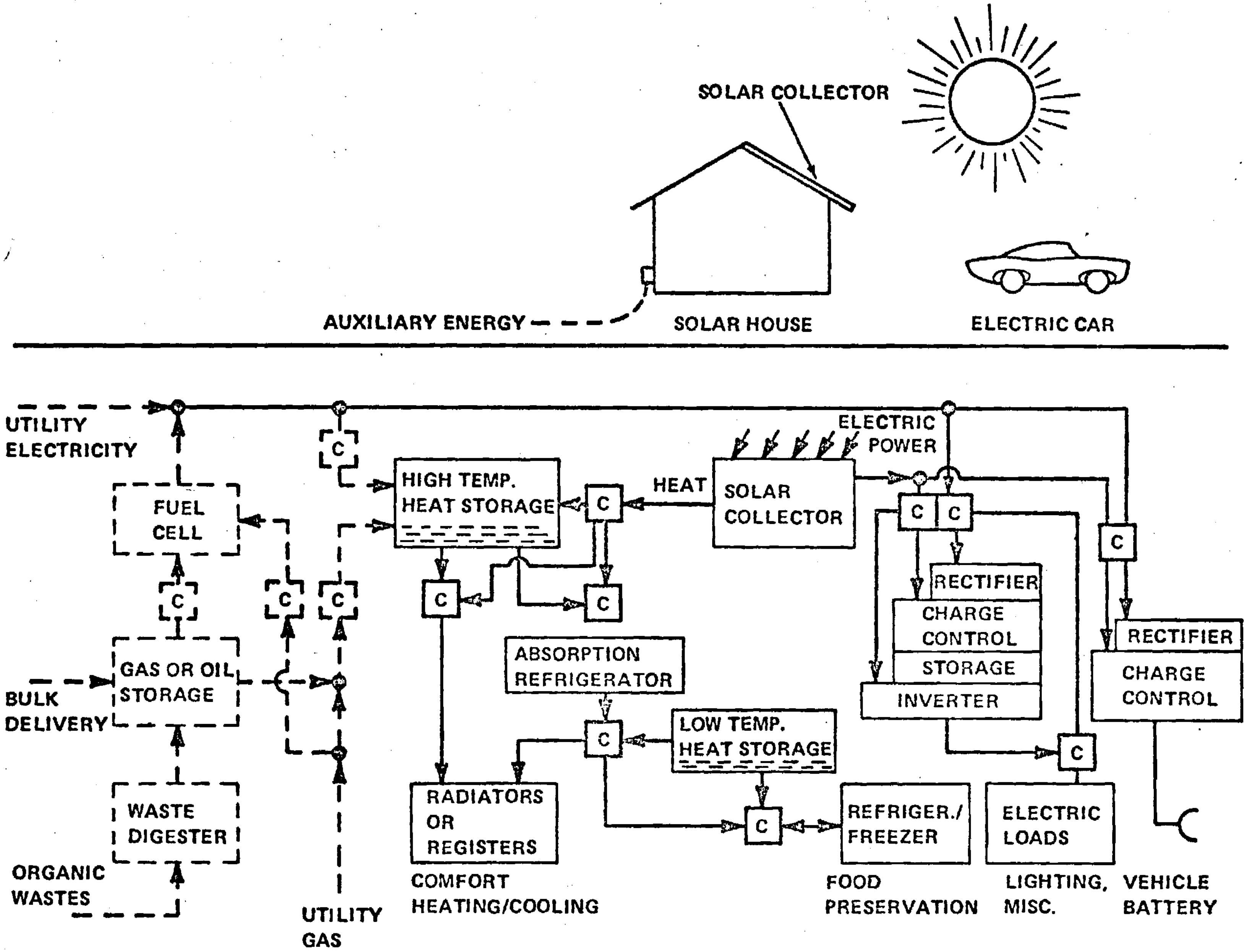


Figure 32. Schematic of a Solar Total Energy System for a Building.

northeastern U. S. This surplus energy could be used for charging an electric automobile. 3) The system is invulnerable to breakdowns in central energy generation stations or transmission systems. 4) The small size of the individual unit makes prototype testing and demonstration relatively inexpensive, and will help to attract consumer oriented industries.

Farber[86] has reported work at the University of Florida on solar water heaters, solar air heaters, a solar still, a five ton solar air conditioner, a solar refrigerator, several solar ovens, a solar sewage digester, solar cell arrays, several types of solar powered hot air engines, solar water pumps, a "solar-electric" car, and a solar house. The solar house, occupied by a graduate student and his wife, uses solar energy for space heating, water heating, swimming pool heating, electricity, and recycling of liquid wastes with the solar still. A 1/3 horsepower hot air engine operating from a 5 foot parabolic concentrator drives a d-c generator to charge the solar-electric automobile to provide pollutionless transportation from the solar house.[87] Thus it has been shown that it is technologically possible to use solar energy to provide all residential energy needs.

If inexpensive solar cells are manufactured, then the major remaining obstacle to the development of total energy systems is the problem of storing the electricity. Backus[88] has proposed a residential solar-cell electric power plant with hydrogen storage. Excess electric power generated during the day is used to electrolyze water to produce hydrogen and oxygen gas, which is compressed into storage tanks, and used in the evening with a hydrogen-oxygen fuel cell. This system is attractive in the long run, but too expensive at present for residential use. Another possible energy storage medium is the flywheel. Rabenhorst[89] has been studying a new type of safe flywheel with an energy storage capacity of 30 watt-hours per pound. Excess electric power generated during the day is used to increase the rotational velocity of the flywheel, and in the evening the energy of the flywheel is used to generate electric power. Lead-acid batteries could be used, but as noted by Loferski[90] "if lead-acid batteries were supposed to store a substantial fraction of all the electrical energy produced in the United States, it is questionable whether enough lead would be available". Other electrochemical systems, however, might be possible, but more research needs to be done.

The other approach to developing a total energy system, not involving solar cells, is to collect the heat at a high temperature using a dynamic conversion system to produce electric power, and use the waste heat for space heating and cooling. Pope[91] et. al, have analyzed four different types of total energy systems using concentrating collectors, high temperature heat storage, and a derated turbine,where the exhaust energy is used for heating and air conditioning. Another system with a flat plate collector driving an organic turbine generator was rejected as not being economically competitive with focused concentrator systems. The analysis used data from Schimmel[92] and Pope's[93] focused collector analyses to calculate the performance and economics of each proposed system for Alburquerque, N.M. One day in four was assumed cloudy and the direct insolation taken to be 80% of the total. The cost of the residential solar energy systems were compared with a "normal" system supplying equal energy demands with utility electric power, and natural gas for space heating, air conditioning, and water heating. The results of these calculations indicat that solar total energy plants with high temperature collection and three levels of heat storage would be economically competitive with the "normal" system when the wholesale fuel cost reaches $0.90/MBTU.

Large users of energy such as apartment complexes, shopping centers, and industries can take advantage of solar-thermal total energy plants ranging in size from 0.2 to 20 megawatts. As of 1972 there were about 550 total energy plants in this size range in operation in the United States[94]. The more recently installed plants have averaged over 5 megawatts in capacity. The electrical storage problems for all types of total energy plants can be reduced considerably if the electric utility company owns and maintains these systems, and allows the excess power generated during the day to be fed back into the utility power grid. The electric power company could then give a credit on the electric bill for power supplied by the customer. The major technical difficulty with this scheme is the phase-matching problem encountered when many different AC sources supply a common grid.

INDUSTRIAL AND AGRICULTURAL APPLICATIONS

The parabolic concentrator has provided an economical means of generating very high temperatures for small scale industrial applications and for research purposes, and solar heat at lower temperatures has been used for both industrial and agricultural drying operations. These represent two of the more promising commercial uses of solar energy.

Solar Furnaces

Trombe [64] developed a megawatt furnace in Montlouis France in the 1950's using heliostats to direct sunlight toward a large parabolic concentrator. Sakurai [95], et.al., built a similar 70 kilowatt furnace in Japan using a 10 meter diameter parabolic concentrator (Figure 33). Another furnace of the heliostat type in Nantick, Massachusetts uses a spherical concentrator.

The Japanese furnace began operation in 1963 and produces temperatures in excess of 3400°C, the melting temperature of tungsten. Refactory bricks have been melted "even in feeble sunlight." The furnace is used for studies of high temperature materials properties and some manufacturing. For example, alumina when melted in a graphite cylinder assumes a spherical shape because of its large surface tension. Turning the cylinder properly results in the formation of a fused alumina crucible which has much more desirable properties than a sintered one. Tungsten melted in an inert gas does not form a carbide even though the melting occurs on a graphite surface. Front surface aluminized mirrors used for the furnace showed a reduction in reflectivity from about 95% to 85% over a five year period. At the present time all the mirrors are aluminized once each year.

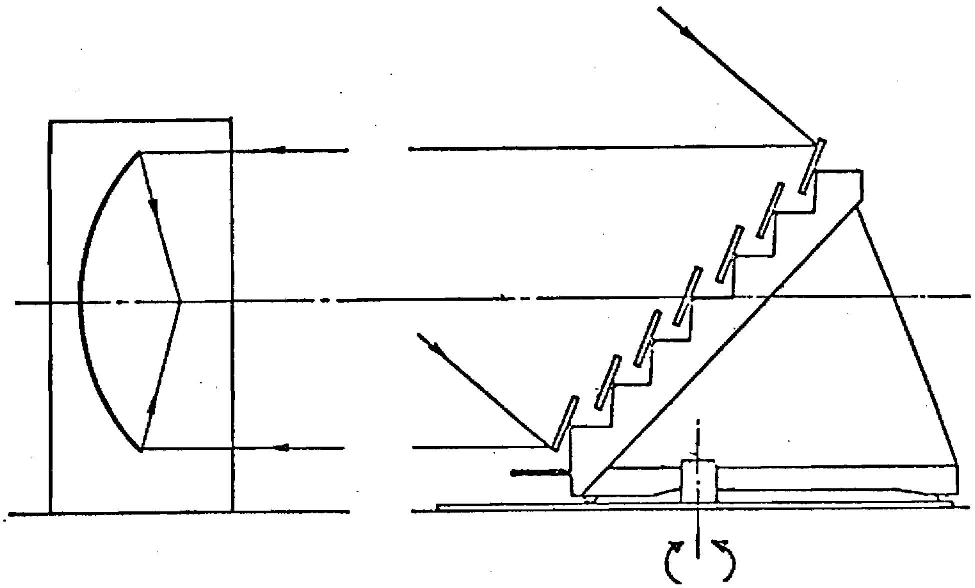


Figure 33. Optical System for a Solar Furnace.

A solar furnace in the Soviet Union "melts refractory materials at a temperature of up to 3,500^{o}C, hot enough to liquify tungsten." [85] It is used for producing high purity refractories.

Air Heaters

Solar air heaters have a great potential for improving agriculturial drying operations around the world. As noted by Akyurt, [96] "A large portion of the world's supply of dried fruits and vegetables continues to be sun dried in the open under primitive conditions. Being unprotected from unexpected rains, windborne dirt and dust, and from infestation by insects, rodents and other animals, the quality is seriously degraded, sometimes beyond edibility. In an increasingly hungering world, practical ways of cheaply and sanitarily preserving foods would be welcome. Solar dehydration has not been fully dealt with by those concerned with solar research."

"Various investigators have experimented with two basic methods of dehydration. In the first method the necessary heat is supplied by directly exposing the material to solar radiation. Aside from its inherent simplicity, this process also enhances the proper color development of greenish fruits by allowing, during dehydration, the decomposition of residual chlorophyll in the tissue under direct solar radiation. The major drawbacks are the possible damage due to overheating, and relatively slow drying rates resulting from poor vapor removal in cabinet driers.

The second method is to heat the foodstuff by circulating preheated air. Since the drying material is not subjected to direct sunshine, caramelization and heat damage do not occur. A further advantage is that the circulating air entrains with it the emerging water vapor, thus accelerating drying. On the other hand, products of inferior appearance may result if immature fruit is dehydrated, since shading prevents the breaking down of chlorophyll."

Akyurt used a square meter area of steel chips beneath a glass cover to absorb solar radiation, and passedair to be heated through the chips. (Figure 34) Steel chips are cheap, have a high heat transfer area per unit volume and excellent turbulance geometries, and an absorptivity of 0.97. Several agricultural products were dried and compared with an open air sun-dried control group. Peppers dried in the solar dryer "possessed attractive bright colors as opposed to the brownish color of the slower drying control batch, which was sun-dried in the open."

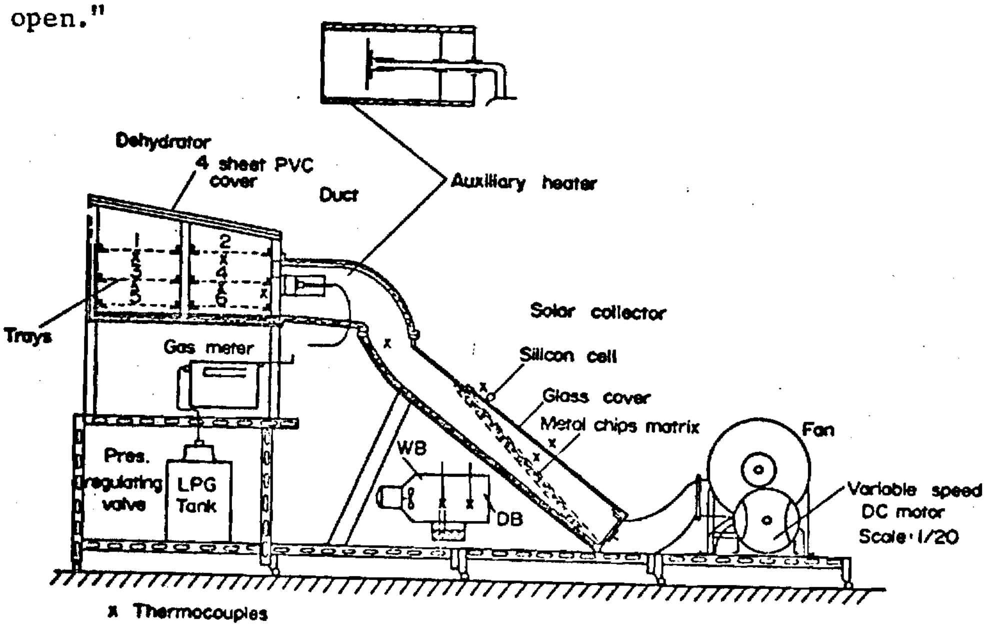


Figure 34. Solar Air Heater [96]

Similarly, "In the dehydration of sultana seedless grapes, the sun dried control sample was rained upon, and hence assumed a dark color. Soon afterwards it was attacked by birds whereupon its weighings had to be terminated. Raisins in the dehydrator possessed a golden color and were dried in spite of continuous rainy weather."

Close [42] has described a variety of types of solar heaters for use in crop drying, space heating, and for regenerating dehumidfying agents. These various types of heaters provide air at 100°F above ambient with collection efficiencies of 50% or more. The heat transfer processes in air heaters are quite differant from those in flat plate collectors which heat water. In the water-cooled collector, heat absorbed is transferred to the water tubes by conduction, so the absorber plate must have a high thermal conductivity. In an air heater the air can be in contact with the whole absorbing surface, so the thermal conductivity of the absorbing surface is of little importance. This makes solar collectors for heating air inherently cheaper than solar collectors for heating water. According to Close, "The main factors determining the efficiency of heat collection of a solar air heater operating at a given air inlet temperature are:

1 Heater configuration; that is the aspect ratio of the duct and the length of duct through which the air passes.

2 Air-mass flow through heater.

3 Spectral reflectance-transmittance properties of the absorber cover.

4 Spectral reflectance properties of the absorber plate.

5 Stagnant air, natural-convection barriers between the absorber plate and ambient air.

6 Heat transfer coefficient between the absorber plate and the air stream.

7 Insulation at the absorber base.

8 Insolation."

Close showed that V-corrugation of the absorber plate considerably improved the performance over that of collectors with flat absorbing surfaces. Spectrally selective coatings also improved profermance. Some of his air heaters of simple construction employing cheap materials were shown to be capable of supplying air at temperatures above 150°F with good efficiency. For crop drying only air temperatures below 180°F are needed.

One study [43] of flat plate air heaters with two glass covers showed that if the air is passed between the two glass panes before passing through the blackened metal collector (two pass) the outer glass temperature is reduced 4°F to 10°F, the collection efficiency increases 10% to 15%, and the temperature rise of the air is increased as much as 20%. Thus, it appears an attractive non-concentrating air heater design would use the two pass configuration and a V-corrugated absorber with spectricly selective coating.

Bevill [97] described tests of air heaters with an absorber consisting of 96 parallel specularly reflecting aluminum fins 6.35 cm high, 0.635 cm apart, and 61 cm long. A single 0.317 cm glass coverplate was placed over the absorber, and air pumped between the fins. The collectors measured 61 cm by 61 cm. The collector with specularly reflecting fins was shown to be about 15% more efficient than an identical collector with diffuse fins. Solar air heaters using hot water from water-cooled flat plate collectors have also been studied[98].

The use of concentrators to produce higher air temperatures for industrial operations, such as the 250° to 500°F needed by textile mills, has received little attention so far. Russell's [67] fixed mirror concentrator, (Figure 27) for example, could be used (as he has proposed) to heat air to high temperatures, and this heat can be inexpensively stored in rocks (Figure 25,26). But instead of using the hot air to generate steam for electric power generation, the air could be used directly for textile drying, and other industrial operations requiring hot air at temperatures up to 1000°F. At $\$4/ft^2$ for the heat supply system, the heat cost is about \$2.00/MBTU, less than many textile mills pay for the propane they are now using.

Solar stills are receiving increasing worldwide use for the production of drinking water from salty or polluted water. A still at the University of Florida [86] is used to reclaim drinking water from household liquid wastes. According to Hay [99] "solar stills remain the cheapest means for desalting quantities of less than 50,000 gal of saline water per day in areas of reasonable sunshine," and production costs are currently about $3.50 per thousand gallons.

A solar still is typically a transparent plastic tent or glass enclosure containing a shallow pan of saline water with a black bottom. Sunlight heats the water in the pan, causing it to evaporate and recondense on the underside of the sloping plastic or glass and run down into collecting troughs along the inside lower edges of the transparent cover. Morse [100] calculated the performance of solar stills under various conditions of ambient temperature and insolation, and his results showed close agreement with data from a 4500 ft^2 solar still located at Muresk in Western Australia (Figure 35).

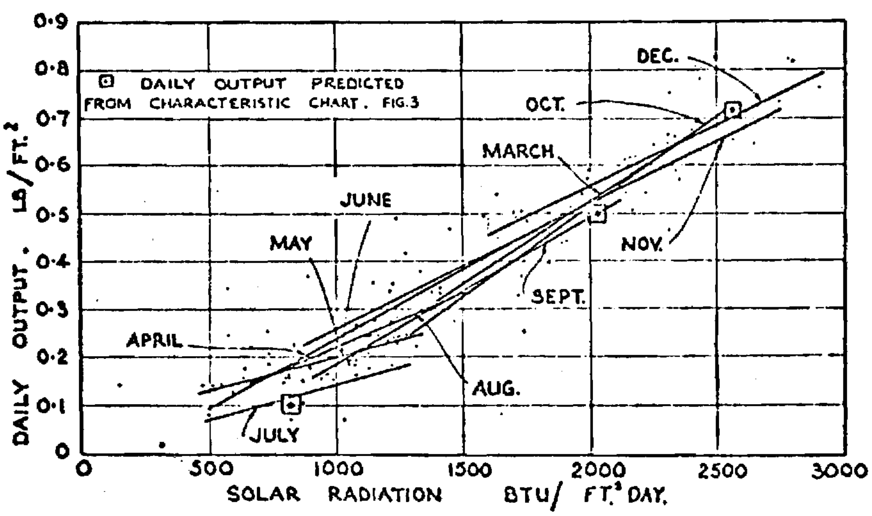


Figure 35. Daily Output of a Solar Still vs. Daily Insolation

The daily output rose from about 0.1 lb/ft^2 (450 lbs. total) of water per day in the winter (July) to about 0.8 lb/ft^2 (3600 lbs. total) of water per day in the summer (December), so the range of production for this still is from 0.012 gallons to 0.1 gallons per day per square foot of collector. Similarly, a large 23,300 ft^2 solar still [101] on the island of Saint Vincent in the West Indes provides the most economical source of fresh water (other than rainwater), since underground natural sources are not available and the cost of shipping water to the island is high. The average daily output of the plant is about 0.05 $gallons/ft^2$ of collector, or more than 1000 gallons per day for the plant. Four mil polyvinyl fluoride film is used as the transparent cover.

Hay [102] has reported the design of a solar still to be mounted on roof-tops (Figure 36). An advantage of this approach is that the cost of the solar

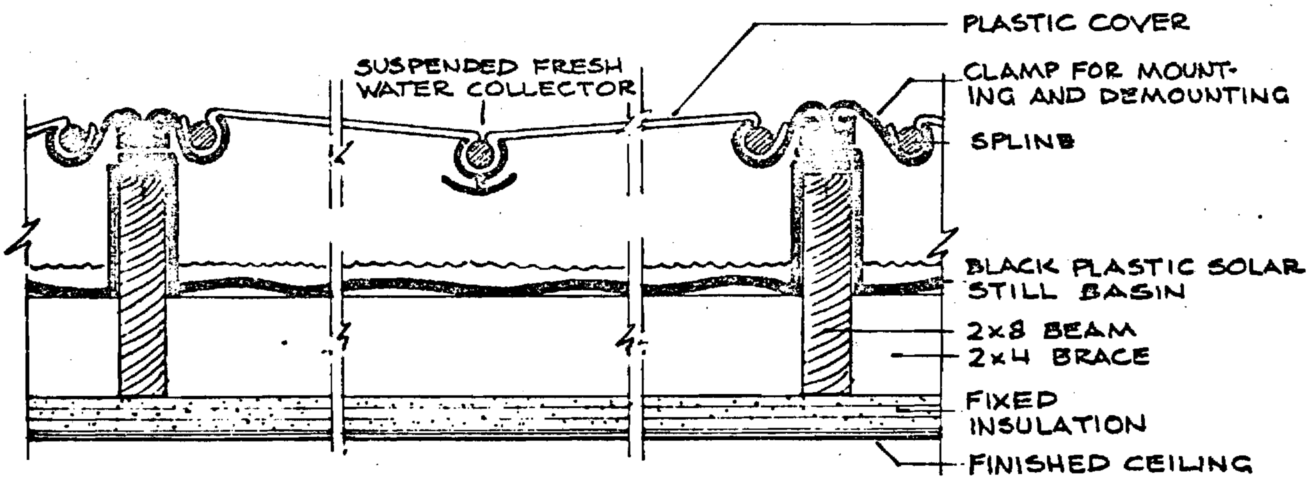


Figure 36. Plastic Rooftop Solar Still[99].

still is partially offset by the savings in ordinary roof costs, since the still replaces the roof. Also, the still is not occupying land area that could be put to other uses. Since solar collectors for space heating and cooling require only about half the roof area, the rest of the roof could be a still to provide fresh water. Shallow depths of saline water are used for maximum yield, so unlike the roof pond, the solar still would add little to the weight of the roof. According to Hay [99] "Several still designs are available with costs approximating those of conventional roofs." The stills use 4 mil polyvinyl fluoride film, treated on the underside for wettability, which should have at least a 5 year life. The inherent safety hazards of glass restrict its extensive use on roofs in densely populated areas, and breakage could cause puncture of the watertight lines with subsequent flooding of the room beneath. With proper design, replacement of the PVC cover every 5 years should be a simple matter. Plastic pipes and fittings would be used to reduce cost and weight.

The still in figure 36 uses a rigid basin of molded resin supported directly on the 2x4 inch braces between the ceiling beams. The PVC transparent cover film is fastened with S-clamps onto the main 2x8 inch roof beams. The weight of the center-suspended condensate collector contributes to the vapor seal and shapes the V-cover so that distillate drains to the collector. The result is an inexpensive waterproof roof which provides a supply of fresh water. Accidental cover damage would, at worst, allow rain to drain into the condensate collector. PVF covers have produced the highest yields for solar stills. [103]

In the Soviet Union large solar stills are used both for industrial and agricultural purposes. A reinforced concrete still was built in 1970 in the Shafrikan collective farm at Bukhere Oblast in the Uzbek Republic. [104] The water in that area was unusable for many purposes because of its very high mineral and sulfur content. With an evaporative area of 6500 ft^2, the still produces a yearly average of 0.08 gallons/ft^2 per day, a total of about 540 gallons per day on the average. The still consists of 39 glass covered independent sections of 168 ft^2 each with a trough depth of 10 cm. The maximum output of 80 gallons/hour occurs between 2 PM and 4 PM (in August) and a minimum output of 5 gallons/hour is produced between 3 AM and 7 AM. Another large still uses steps inclined at a 2^o to 3^o angle so the water flows over the steps,from upper to lower, until it reaches the discharge drain. This flow enhances evaporation and increases the output and efficiency of the still about 20%.[105]

The Krzhizhanovsky Power Institute in Moscow has also been studying various aspects of solar stills. Baum[106] conducted theoretical studies of heat and mass transfer processes in solar stills of the hotbox type and developed techniques for calculating the performance of these stills. He described the basic process occurring in these solar stills as follows. "In an adequately designed still the greater portion of the solar energy that passes through the glass (or film) is spent on evaporation of saline water. As a result, the space within the still is filled with a steam-air mixture. The energy-balance conditions during operation of the still are such that the surface of the glass is at a lower temperature than that of the steam-air mixture, with the result that water vapor condenses on the glass surface, whereas the condensate runs down the inclined glass, drips into the groove and is collected in the tank." He constructed a very well instrumented solar still to investigate these processes. During the tests the temperature of the water heated by the sun varied from 74^oF to 207^oF while the temperature of the glass condensing surface varied from 61^oF to 192^oF. As a result of these studies Baum developed equations which accurately describe heat and mass transfer processes in this type of solar still.

Annaev[107] studied the effect of wind speed and direction on the output of a solar still of the greenhouse (glass) type by using a fan to blow air across a small still. For saline water temperatures of 104°F, 131°F and 158°F the wind speed was varied from 0 to 26 feet/sec at wind directions of 0, 45, 90, 135 and 180°; and for all wind directions and temperatures the maximum still output was achieved for a wind velocity of about 16 ft/sec. The reason is that increasing the wind velocity up to this value increases the rate of heat removal from the glass cover, which increases the rate of condensation on the glass resulting in an acceleration of the evaporation process and as much as a 25% increase in still output. Further increases in wind speed lead to a reduction in the saline water temperature which reduces the evaporation rate and still output. The most favorable wind direction is parallel to the condensing surfaces (80° angle). Annaev's data is presented in a table "which can be used for estimating purposes in designing solar stills for a specific site."

CLEAN RENEWABLE FUELS

Most of the energy used in the United States today comes from fossil fuels produced many years ago from solar energy. Clean renewable fuels to supplement and eventually replace these fossil fuels can be produced from plant life grown under more optimum conditions than found in nature, and from organic waste materials. The various processes for the production of these fuels listed in figure 37 are aimed at converting organic materials with a low heating value per unit weight into higher heating value fuels similar to the fossil fuels currently in use. Another possible technique is the use of high temperature heat from solar concentrators to operate a regenerative thermochemical cycle for the production of hydrogen; the hydrogen can be used directly or utilized for the production of hydrocarbon fuels such as methane.

Perhaps the oldest and simplest technique for the production of a clean renewable fuel is to grow plants and burn the plants for energy. Szego [108] has proposed that this be done on a large scale for electric power generation. Air pollution from such a plant is minimal since virtually no oxides of sulfur are produced, particulate emissions can be controlled with precipitators, and the CO_2 released is reabsorbed by the growth of new plants. Up to 3% of the incident solar energy can be absorbed by plants [13, 109], and this energy is released when the plants are burned. For a 1000 MWe steam-electric power plant operated at a load factor of 75% with a thermal efficiency of 35%, 150 square miles of land area is required to fuel the plant if the average insolation is 1400 BTU/ft^2 - day and the capture efficiency of the plants is 3%. Szego [108] calculated the total cost of the fuel to be \$0.06/MBTU for a \$250/acre land cost, 1400 BTU/ft^2 - day insolation, 3% capture efficiency, 8% interest rate, 0.6% tax rate, and \$200/acre harvesting cost, and the total cost of the electric power

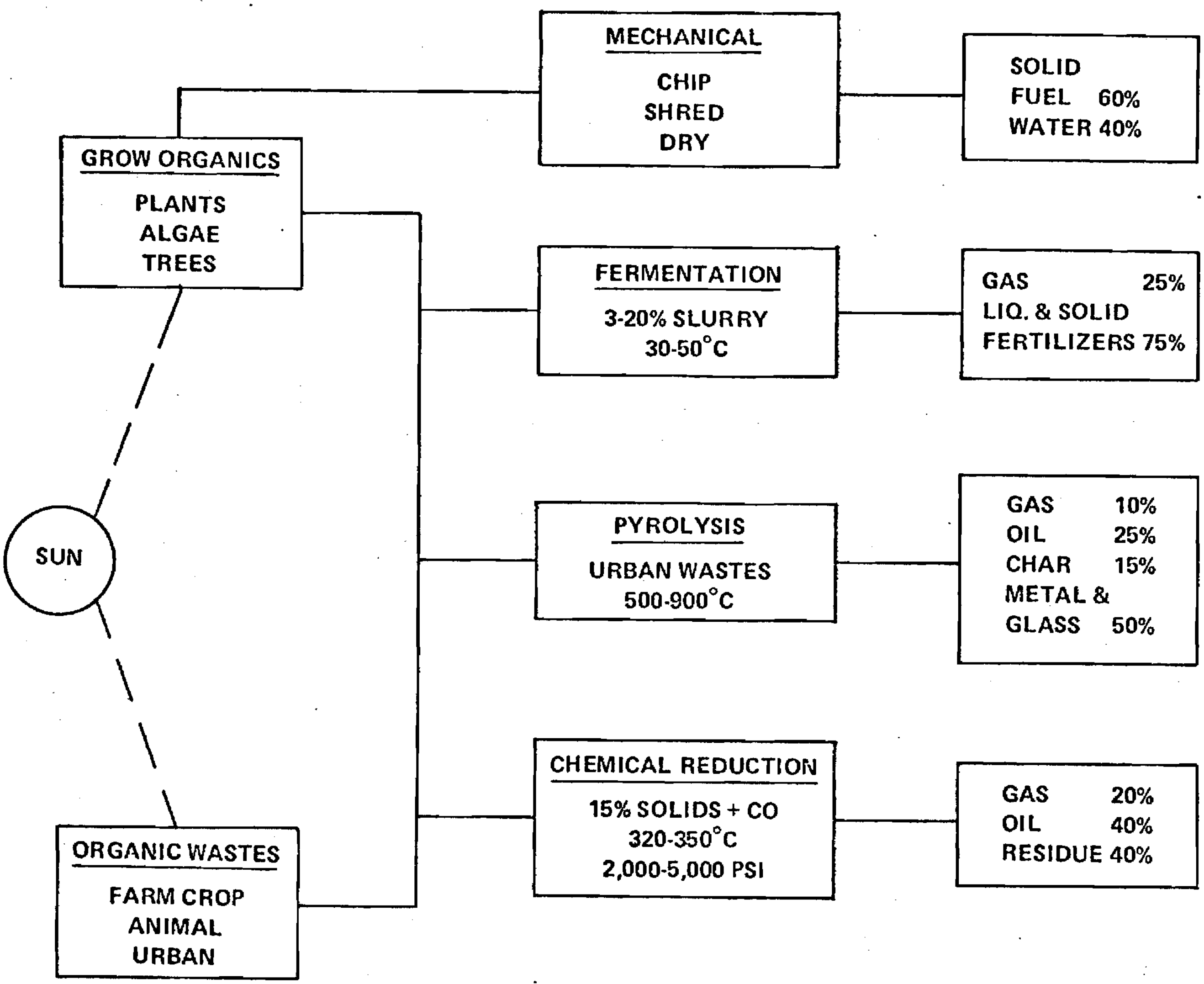


Figure 37. Processes for Producing Fuels from Solar Energy [13]

from this "energy plantation" is computed to be 5 mills/KWh, based on a $200/KW capital cost and 28 year life for the power plant. A "worst case" fuel cost is $0.40/MBTU if the capture efficiency is reduced to 1% and the harvesting cost increased to $700/acre, which results in a power cost of 8.5 mills/KWh. The annual operating cost is taken to be $2 million/year, and insurance and tax costs 0.12% and 2.35% of the capital cost of the power plant. Szego concluded that this type of plant would "cost no more to build and maintain than a conventional fossil fuel steam electric plant" and that "the energy plantation is a renewable resource and is an economical means of harnessing solar energy." It is not at all obvious at the present time what type of plant (trees, grasses, etc.) will result in the lowest power costs. The NSF/NASA Solar Energy Panel[13] concluded that using trees the fuel cost at the power plant might range from $1.50 to $2.00/MBTU.

Some power can also be produced by the combustion of organic wastes, which also reduces problems of disposal of these wastes. It has been estimated[13] that the total animal and solid urban wastes which can be collected at reasonable cost could provide about 6% of the heat energy requirements for electric generating plants. The most promising use of solid animal wastes is in connection with large feedlot operations where large quantities are accumulated at one location and disposal presents a continuing problem.

Anaerobic fermentation of organic materials results in the production of methane and carbon dioxide. This process can be used (Figure 38) to convert from 60% to 80% of the heating value of organic materials into methane, which can serve a wide variety of uses including powering automobiles. Methane can also be used in existing natural gas pipelines. Algae grown in sewage ponds can also be used for the production of methane; costs of producing methane by this method are estimated between $1.50 and $2.00/MBTU.[13]

Pyrolysis has also been used for many years to convert organic materials to gaseous, liquid and solid fuels. Any organic materials can be used, and in addition plastics, rubber products, and other similar materials can also be used. The gases produced are a mixture of hydrogen, methane, carbon monoxide, carbon dioxide, and hydrocarbons. About two barrels of oil can be produced per ton of dry organic material. A plant handling 1000 tons of waste per day (Figure 39) could dispose of the solid wastes produced by a city of 600,000 people.

At temperatures around 600°F and pressures between 2000 psi and 4000 psi organic materials can be partially, converted into oil. In laboratory tests oil yields up to 40% of the weight containing about 2/3 of the heating value

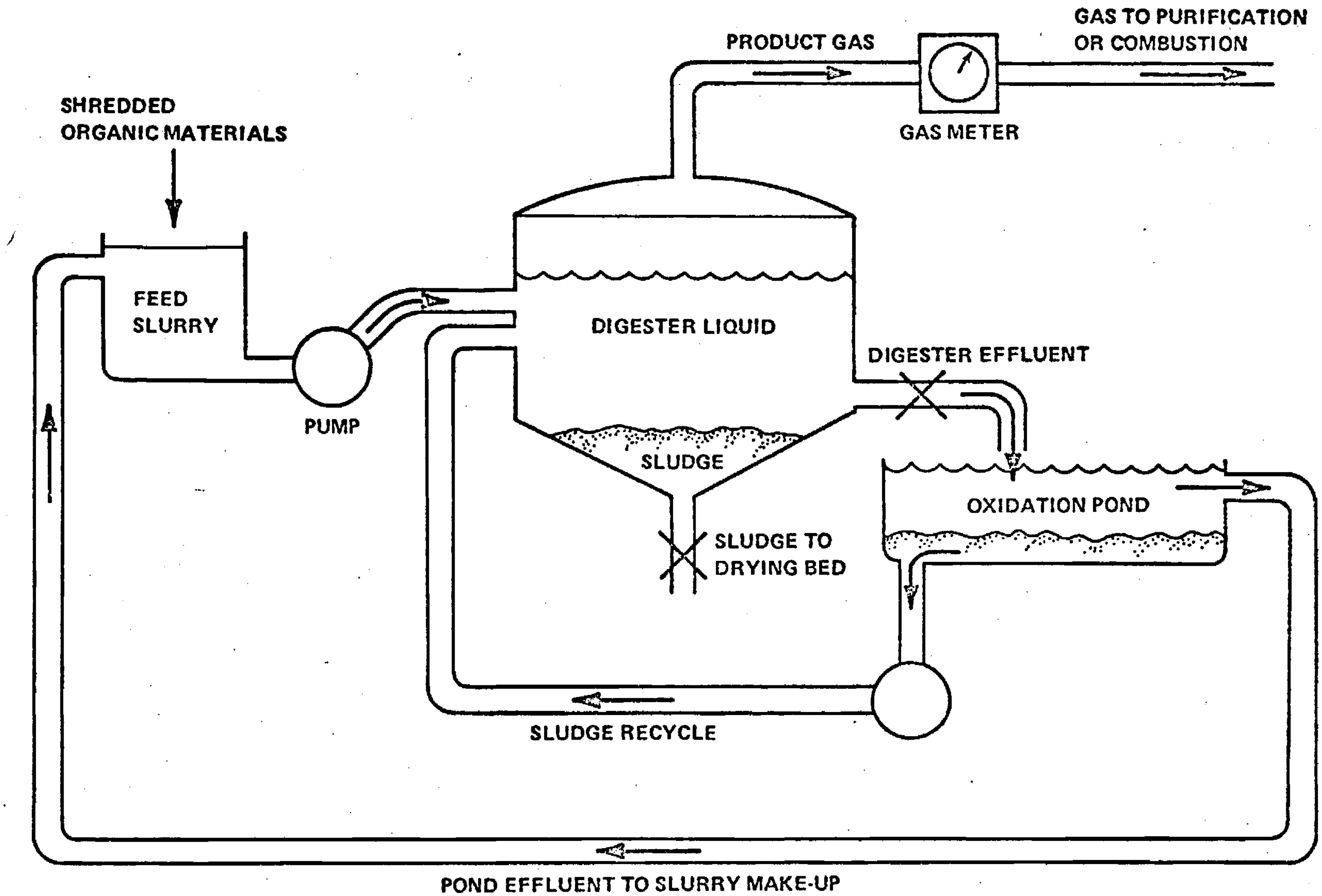


Figure 38. Anaerobic Fermentation System For the Production of Methane[13].

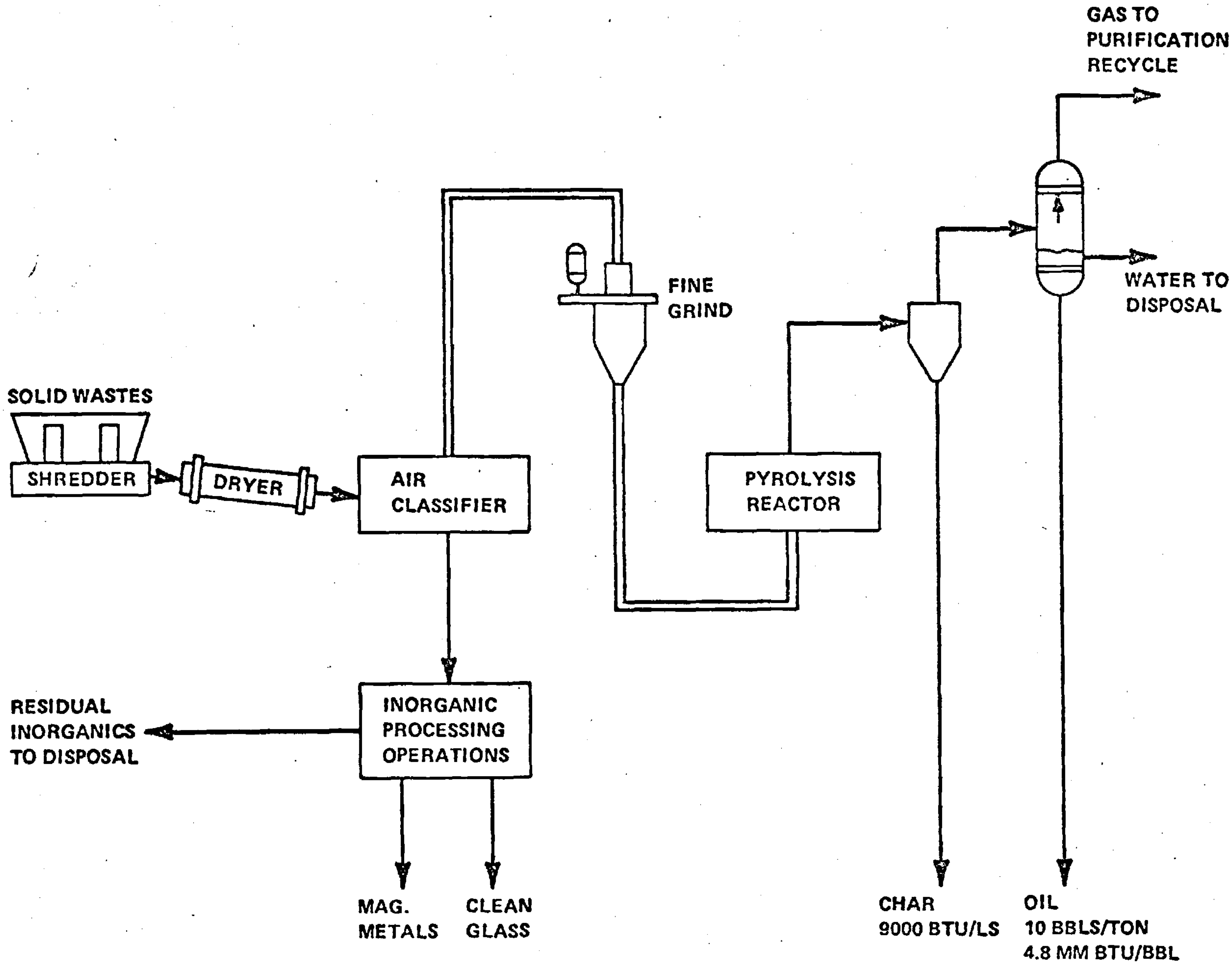


Figure 39. Schematic of Solid Waste Pyrolysis Plant[13].

of the initial dry organic matter have been obtained.

Hydrogen may be thermochemically produced directly from water using solar heat. For example a regenerative chemical cycle proposed by DeBeni[110] operates with bromides of calcium and mercury in a four step process with a maximum temperature of 1350°F. The four reactions are

1)	$CaBr_2 + 2H_2O$	$\rightarrow$	$Ca(OH)_2 + 2HBr$	1350°F
2)	$Hg + 2HBr$	$\rightarrow$	$Hg\ Br_2 + H_2$	480°F
3)	$HgBr_2 + Ca(OH)_2$	$\rightarrow$	$CaBr_2 + HgO + H_2O$	400°F
4)	HgO	$\rightarrow$	$Hg + (0.5)O_2$	900°F

The net result of these four reactions is:

$$H_2O \rightarrow H_2 + (0.5)O_2$$

Water is thus seperated into hydrogen and oxygen at temperatures easily obtainable by linear concentrators in large solar farms. The hydrogen and oxygen are released at separate points in the cycle, and the chemicals used are regenerated permitting virtual 100% recovery of the chemicals without sideloops. One drawback is the large amount of materials circulation per unit product. This cycle is an example of a number of regenerative thermochemical cycles that have been proposed for the production of hydrogen with temperatures obtainable on a large scale with solar concentrators.[111]

Figure 40 illustrates the relative 1972 cost of solar-produced clean renewable fuels and fossil fuels. The costs of fossil fuels are now rising rapidly, so solar synthetic fuels are going to continue to become increasingly competitive.

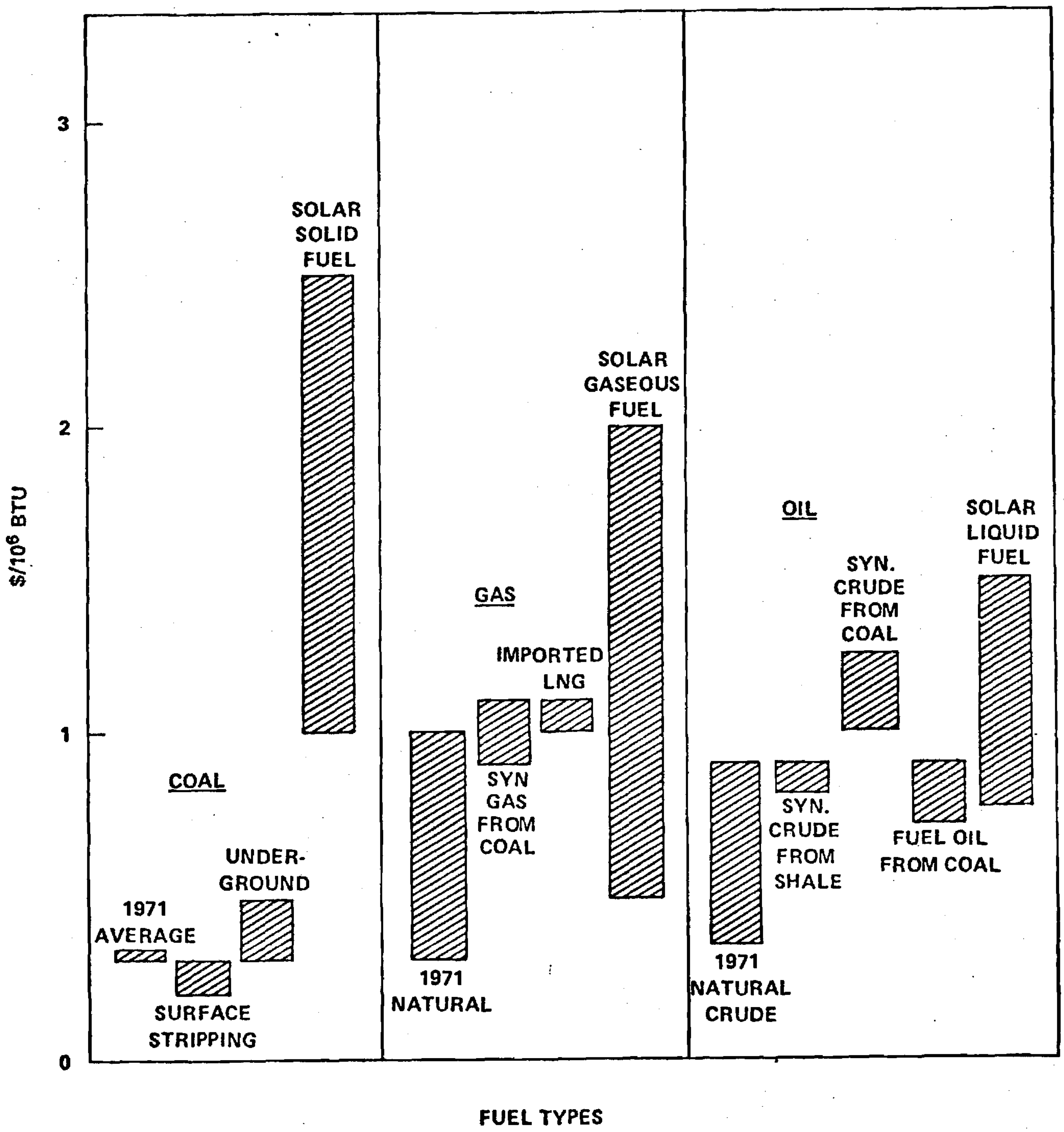


Figure 40. 1972 Costs of Fossil and Solar Renewable Fuels.

OCEAN THERMAL POWER

The French physicist Jacques D'Arsonval [112] suggested in 1881 that a heat engine operating between the warm upper layer and the cold deep water of the tropical oceans could produce large amounts of power. Although the engine must be inherently inefficient, the amount of heat available is enormous, and since this heat comes from the sun, ocean thermal power is appropriately classified as a form of solar power. D'Arsonval suggested a number of possible high vapor pressure working fluids, including ammonia.

In 1929 Claude [113], a friend of D'Arsonval, demonstrated a 22 kilowatt ocean thermal power plant in Mantanzas Bay, Cuba (Figure 41), but due to its low efficiency (< 1%) the plant was not economically competitive with other power plants at that time. Claude used surface sea water admitted to a low pressure evaporator to provide low pressure steam to drive the turbine. This low pressure steam was then recondensed by direct contact with cold seawater in a spray condenser. The Claude cycle avoided large heat exchangers required by closed cycle plants to vaporize and recondense a high vapor pressure working fluid, but did require a large turbine of inherently low efficiency. The relatively high vacuum required maintaining large leak-tight connections and the removal of dissolved gases from the water. The plant itself was located on land and 2Km long tubes brought cold water from the depths, with resulting heating of the water as it flowed through the tubes. In spite of the economic failure of the project, Claude's plant was the first to demonstrate power generation from ocean temperature gradients.

Two large experimental power plants of 3.5 MWe each using the Claude cycle were built by the French at Abidjan off the Ivory Coast in 1956 to utilize a thermal differance of 36°F. An 8 foot diameter pipeline was built extending to a depth of 3 miles about 3 miles from shore, but difficulties in maintaining this pipeline prevented the plant from operating at full capacity. About 25%

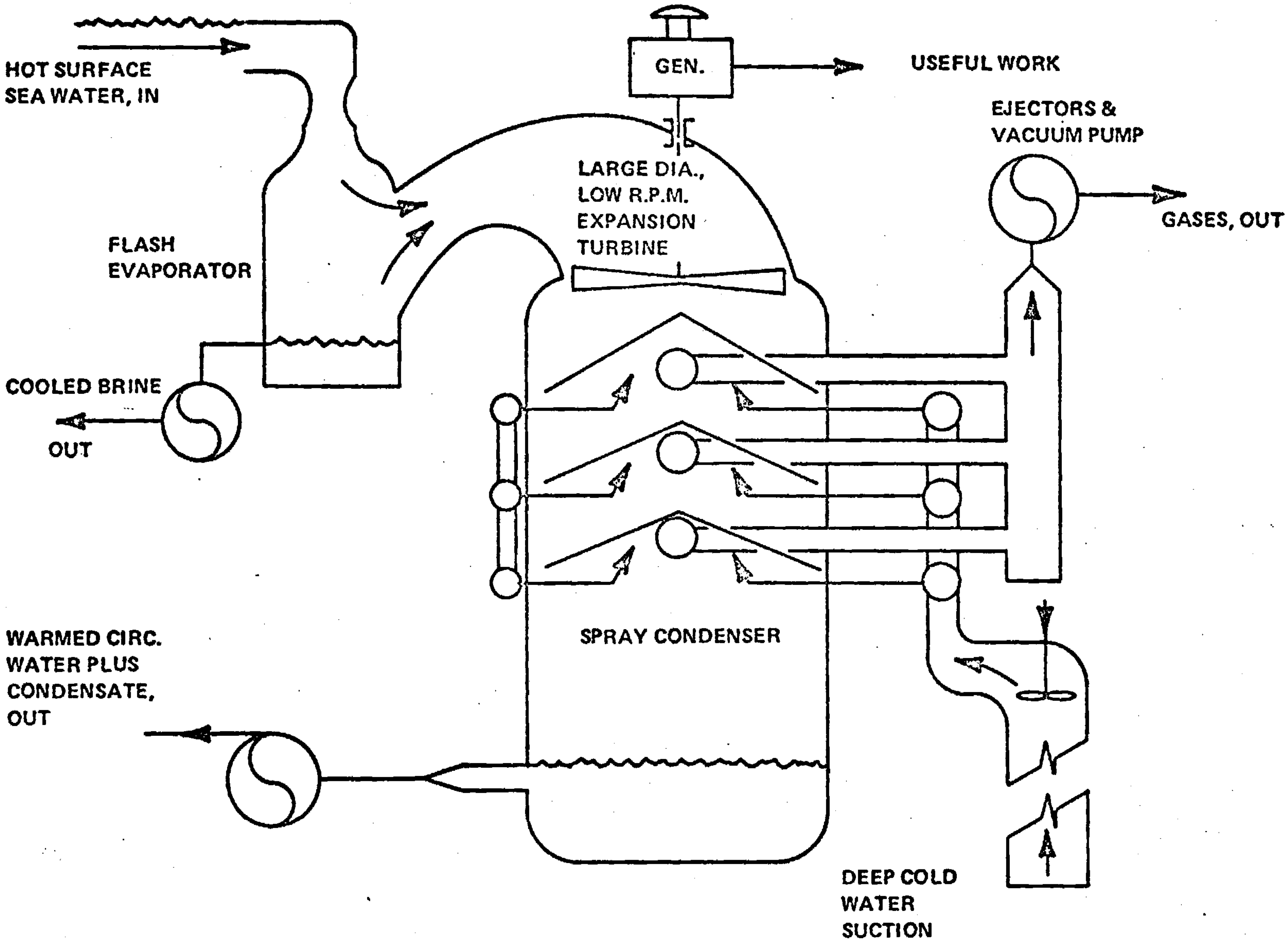


Figure 41. Claude's Ocean Thermal Power Plant

of the power generated was required for the pumps and other plant accessories. The plants were finally abandoned.

Two approaches to improving the Claude cycle are the use of controlled flash evaporation as proposed by Roe [114], and the indirect vapor cycle proposed originally by D'Arsonval. Roe's system (Figure 42) illiminates major problems of deaeration and seawater corrosion associated with the Claude cycle and produces fresh water in addition to electric power. The flash evaporator consists of a large number of parallel vertical chutes with films of warm seawater flowing down (Figure 42). As the pressure drops, water evaporates and the vapor flows downward. This low pressure steam then flows

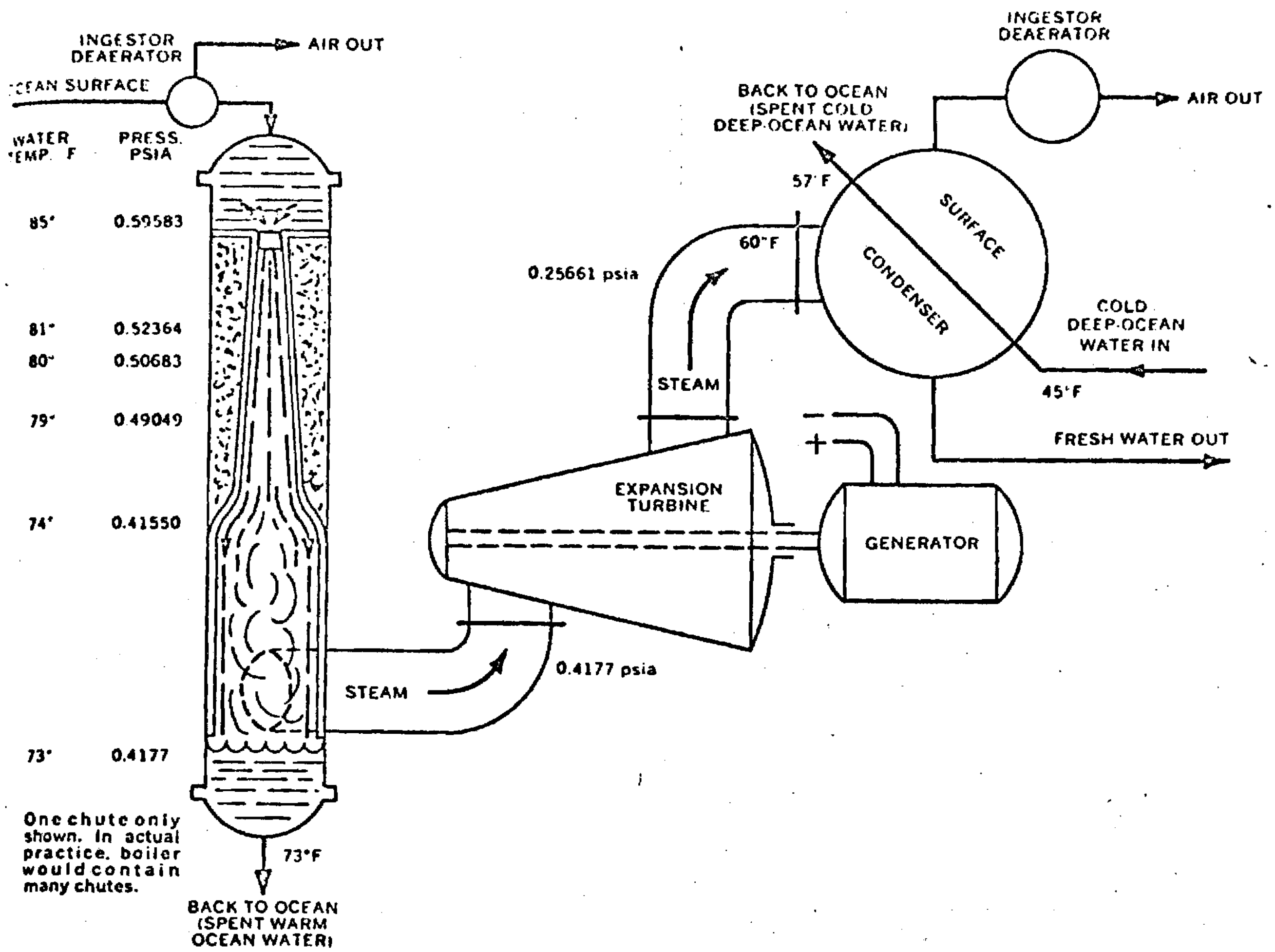


Figure 42. Controlled Flash Evaporation Ocean Thermal Power Plant [115]

through the large low pressure turbine and into the condenser where it is cooled and condensed by cold seawater from the ocean depths. If fresh water is not desired, steam from the turbine can be condensed by direct contact with cold seawater (as in the Claude cycle) with a slight increase in power output. Deaeration in this cycle is accomplished at a low cost with practically no power requirement. About 11.5 gallons of pure water can be produced per 1000 gallons of warm water circulated.[115] This system still suffers from the large, inherently inefficient low pressure steam turbine.

The indirect vapor cycle requires the addition of a boiler, but permits the use of higher pressure working fluids with a much smaller and more efficient turbine. Since the efficiency of ocean thermal plants will be only about a tenth that of modern steam plants, the amount of heat transferred in the boiler and condenser per unit power output must be about ten times as large. It does not follow, however, that the costs of these components will be ten times as great. Since ocean thermal plants will operate at relatively low pressures and ambient temperatures, the tube wall can be thinner and cheaper materials can be used, so the cost per unit of heat transfer should be much less for ocean thermal boilers and condensers than for those used in high temperature steam plants.

Anderson[116] proposed a floating power plant using propane as the working fluid (Figure 43). Seawater from the warm surface layer is passed through the boiler to vaporize propane at about 150 psi. The propane exhausted from the turbine is condensed at about 110 psi by cold seawater. In 1965 the Andersons estimated the capital cost of this plant at $168/KW, which was comparable to the capital cost of a fossil-fueled plant at that time. In order to equalize pressure differances in the boiler and condenser, the Andersons proposed that the plate heat exchanger acting as the boiler be lowered to a depth of 290 feet and the plate condensers lowered to 150 feet, with the turbines and other components at intermediate depths. Zener[117] has suggested a modular design

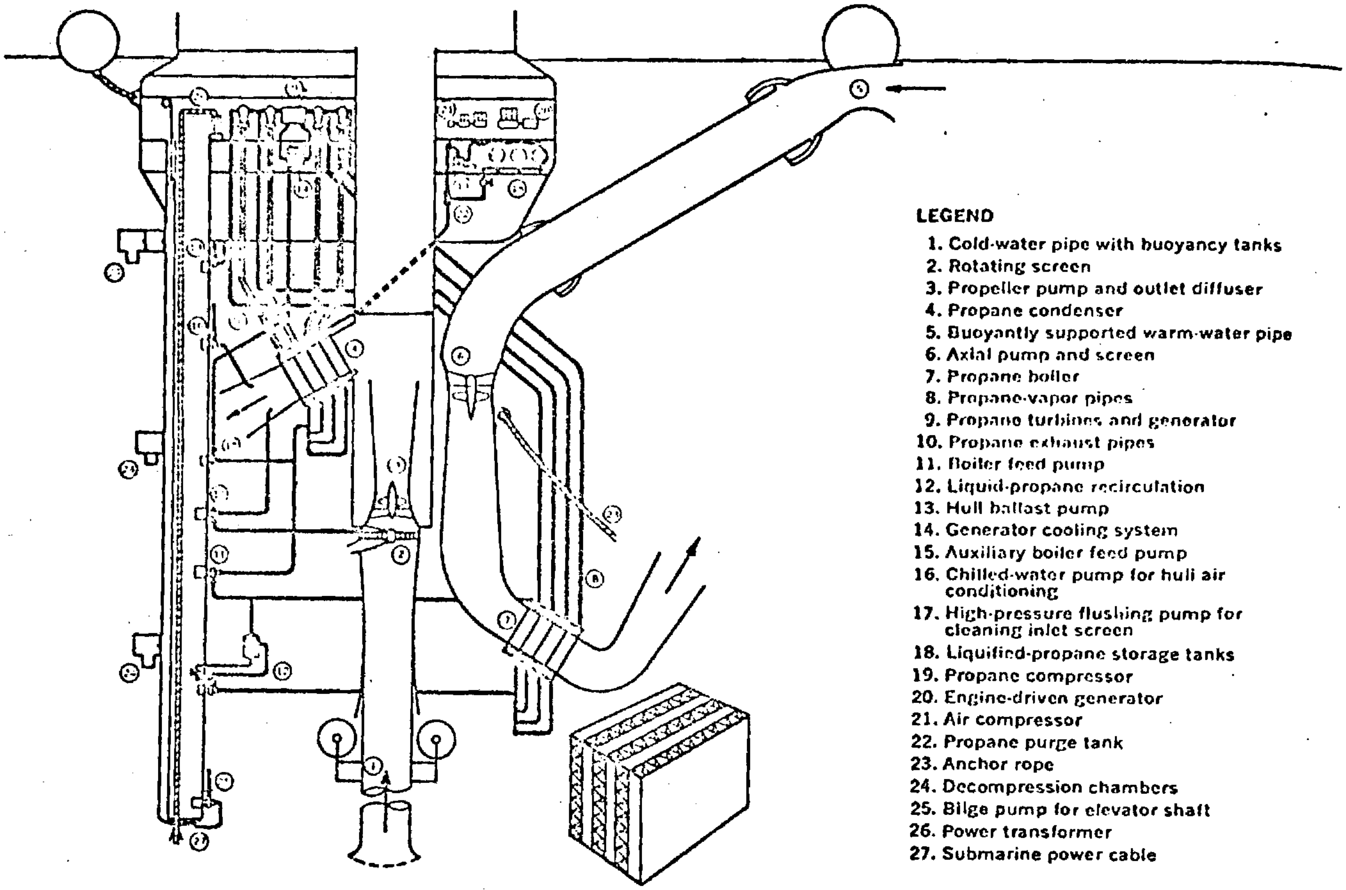


Figure 43. Floating Propane Ocean Thermal Power Plant [115]

with the boiler, condenser and engine modules all of the same standard size, such as 8 ft by 8 ft by 40 feet (Figure 44). The modular system should reduce manufacturing, transportation, and assembly costs. The plant would be nentrally buoyant at the depth which minimizes the pressure differances in the boiler and condenser.

McGowan [118] et. al. with NSF/RANN support have conducted an analysis of ocean thermal power plant concepts from 100 to 400 MWe using various working fluids. Figure 45 is a schematic of their system and a generalized temperature entropy diagram; characteristics of potential working fluids are given in Table 8. The ideal cycle efficiency in Table 8 is based on a maximum cycle temperature of 65°F and a minimum cycle temperature of 45°F. Ammonia is the best working fluid from the heat transfer standpoint. McGowan [118] presents a comparison of the other working fluids with ammonia as follows:

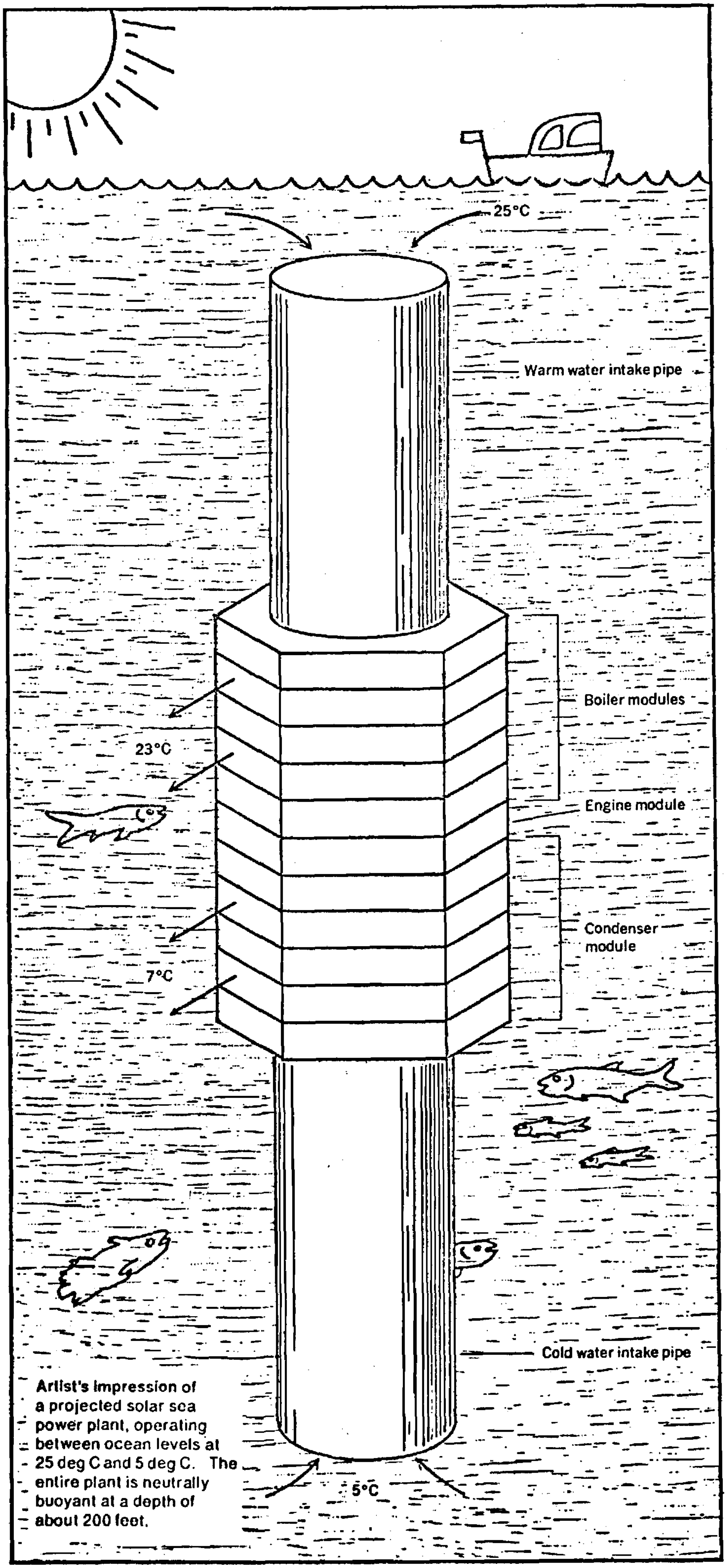


Figure 44. Modular Ocean-Thermal Power Plant[117]

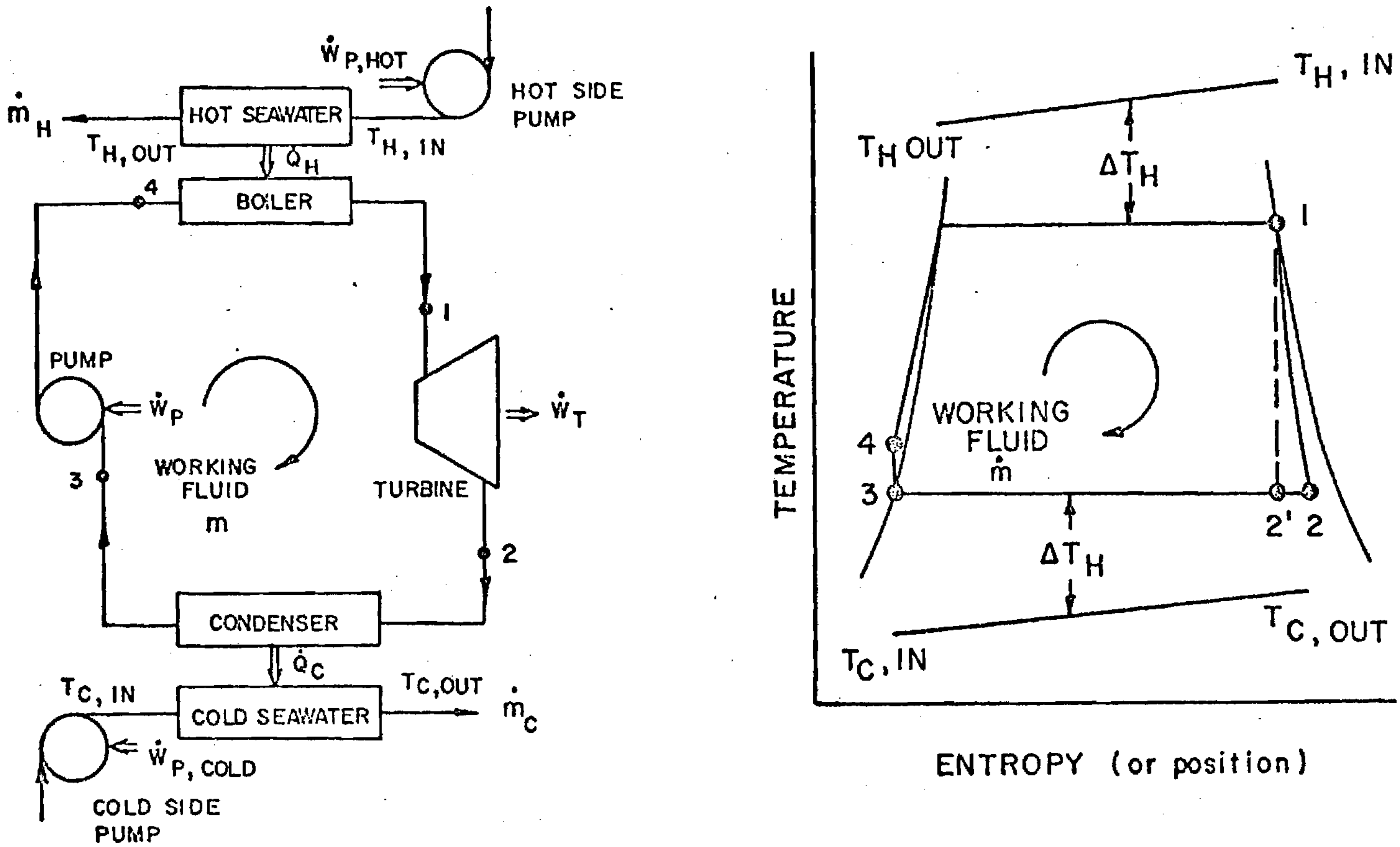


Figure 45. Schematic and T-S Diagram for Ocean Thermal Power Plant [118]

Table 8. Comparison of Working Fluids[118]

FLUID	IDEAL CYCLE EFFICIENCY (%)	CYCLE EFFICIENCY (5% ΔP/P)	HIGH PRESSURE (psia)	LOW PRESSURE (psia)	PUMP WORK (kw)	IDEAL MASS FLOW (lb/min)
Ammonia	3.72	2.71	118	81	1079	317,600
Butane	3.82	2.81	29	20	859	976,000
Carbon Dioxide	2.89	1.67	799	609	36,033	2,873,000
Ethane	3.90	2.04	53	411	25,300	1,495,000
R-12	3.68	2.57	78	56	2,450	2,630,000
R-22	3.68	2.54	126	91	3,200	1,978,000
R-113	3.65	2.91	5	3	170	2,436,000
R-500	3.67	2.55	92	66	2,750	2,205,000
R-502	3.61	2.41	140	103	4,552	2,756,000
Propane	3.67	2.46	115	85	3,706	1,084,000
Sulphur Dioxide	3.72	2.82	45	30	634	1,041,000
Water	3.78	3.26	0.3	0.15	1.4	155,500

Table 9. Heat Transfer Coefficients of Working Fluids

FLUID	RELATIVE h condensing	RELATIVE h boiling
Ammonia	1	1
Butane	0.15	0.32
Carbon Dioxide	0.18	0.18
Ethane	0.11	0.21
R-12	0.11	0.11
R-22	0.16	0.14
R-113	0.09	0.13
R-500	0.12	0.13
R-502	0.10	0.11
Propane	0.13	0.27
Sulphur Dioxide	0.38	0.33
Water	0.92	2.27

They also considered a variety of heat exchanger geometries illustrated by Figure 46. For ammonia a single stage turbine with a 7 foot wheel diameter would generate 25 MW at 1800 RPM, for propane a 12 foot wheel diameter single stage turbine could produce 30 MW at 600 RPM. Propane and ammonia appear at present to be the most attractive working fluids.

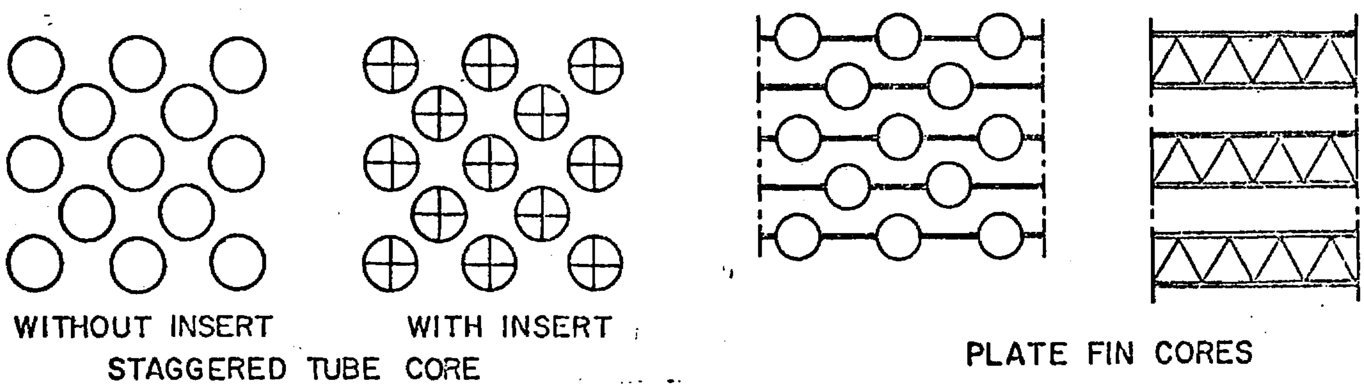


Figure 46. Potential Heat Exchanger Geometries

The amount of energy available for ocean thermal power generation is enormous, and is replenished each year as the sun heats the surface layers of oceans and melts snow in the arctic regions causing cold currents to flow deep beneath the surface toward the equater. According to Zener, "the tropical oceans in the year 2000 could supply the whole world with energy at a per capita rate of consumption equal to the US per capita rate in 1970 and suffer only a one-degree C drop in temperature." Also, if nutrient-rich cold water is brought from the ocean depths and released near the surface, this could result in a substantial increase in fish populations, as occurs naturally off the coast of Peru. Another advantage could be a slight lowering of tropical temperatures. Figure 47 gives the surface and underwater temperatures in the straits of Florida just 30 miles from Miami. At a depth of 1300 feet the temperature is $43^{o}F$, as compared with a surface temperature from $75^{o}F$ to $84^{o}F$.

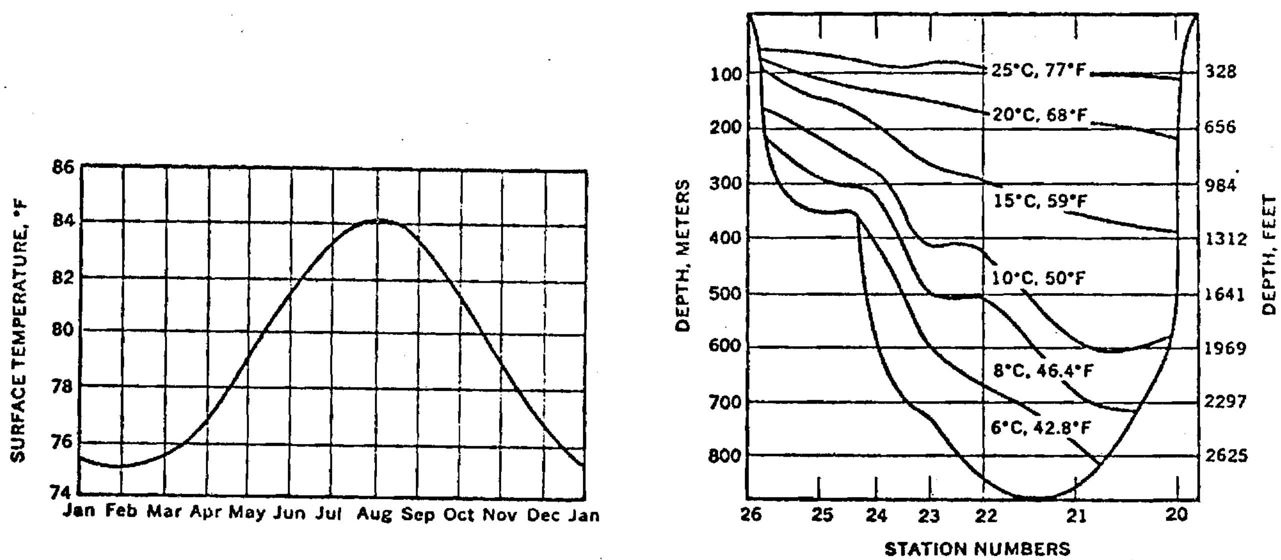


Figure 47. Water Temperatures in the Straits of Florida. [115]

Anderson [119] has recently proposed an "sea plant" with a floating propane cycle ocean-thermal electric power plant, a separate ocean-thermal flash - evaporation plant for producing pure water, and various chemical industries based on extracting oxygen and new materials from the ocean. Noting that the Gulf Stream alone could supply 200 times the total power requirements of the United States, he estimates the cost of a 100 MWe plant at $20 million

($200/KWe) and cost of fresh water at $0.04 per thousand gallons. This cheap power and cheap water makes possible a variety of energy intensive chemical process plants. Oxygen gas, extracted from seawater, could be liquified using propane turbines to drive the refrigeration compressors, and cold water from the ocean can be used as a convenient heat sink at lower than usual ambient temperatures. Chemical plants using raw materials extracted from seawater would benefit from the cheap power. Bromine and magnesium are already being produced commercially from seawater [120]. In addition, one of the best ways to transmit power to shore may be to electrolyze water to produce hydrogen and oxygen, and then liquify these gases, which can then be shipped or piped to shore. Anderson concluded that "sea thermal power is potentially a profitable enterprise. At this stage of development it appears to have far better economic potential than any other scheme to utilize solar energy for power production."

GEOSYNCHRONOUS POWER PLANTS

The concept of placing a large solar array in geosynchronous orbit and transmitting this power to earth was proposed by Glaser [121, 122] in 1968, and since has received increasing attention as a potential major energy resource for the next century. The basic motivation for placing the solar array in space is the increased availablity of solar energy in space, as illustrated by Table 10. Fifteen times as much solar energy is received

Table 10 - Average Availabilities of Solar Energy [123]

AVAILABILITY FACTOR	AVERAGE ON EARTH	IN SYNCHRONOUS ORBIT	AVERAGE RATIO
Solar Radiation Energy Density	0.11 watts/cm^2	0.14 watts/cm^2	4/5
Percentage of Clear Skies	50%	100%	1/2
Cosine of Angle of Incidence	0.5	1.0	1/2
Useful Duration of Solar Irradiation	8 hr.	24 hr.	1/3
PRODUCT			1/15

by a solar array in space as the same array would receive on the ground, and this energy is received continuously, 24 hours a day. Now that NASA is developing the space shuttle to permit the routine exploitation of the space enviroment, the economics of geosynchronous power plants are becoming more attractive.

The basic concept, as proposed by Glaser, is illustrated by Figure 48. concentrators would reflect sunlight onto an advanced, lightweight solar array. The two symmetrically arranged collectors convert solar energy directly to electricity which powers microwave generators with the transmitting antenna located between the two large collecting panels. The 1 Km diameter antenna transmits the power to a 7.4 Km diameter receiving antenna on the ground (Figure 49) with an overall efficiency of about 68%. The microwave transmission system is expected to cost \$130/KWe.[125] In order to achieve the

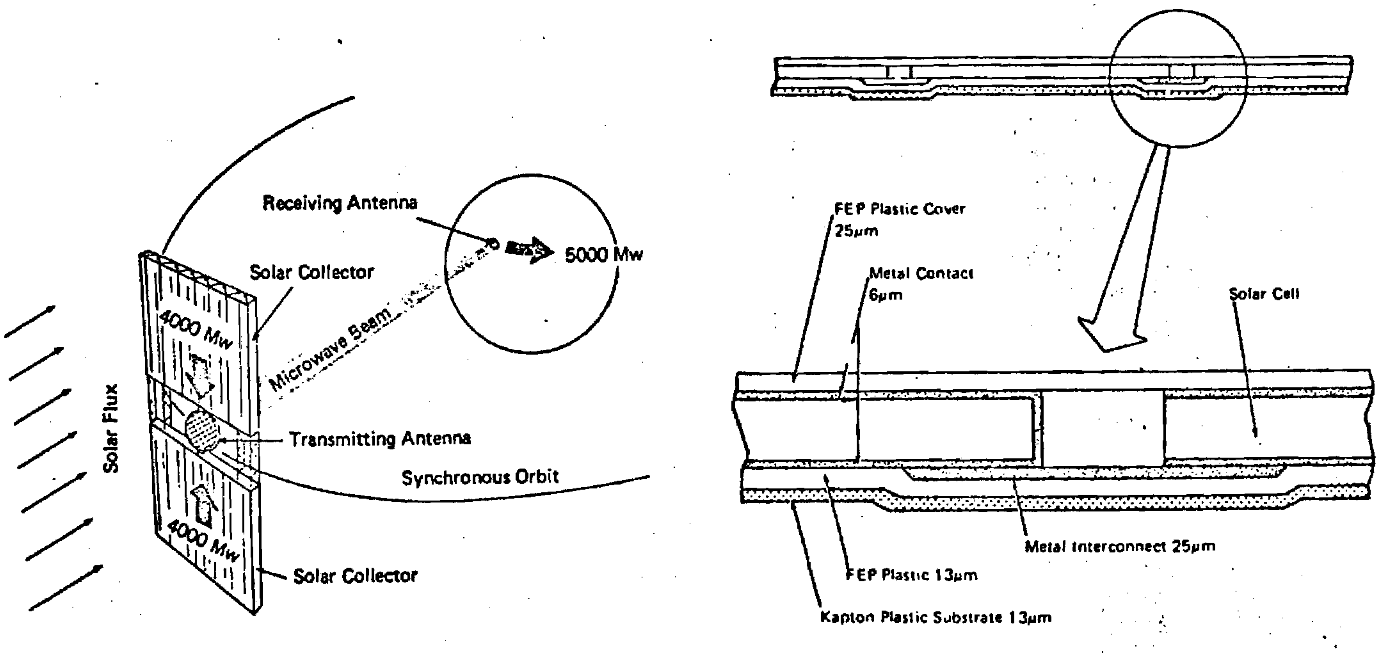


Figure 48. A) Geosynchronous Solar Power Plant [124]
B) Solar Cell Array Construction [125]

necessary coherent transmission, the many separate elements of the transmitting antenna must be phase locked onto a pilot signal originating from the center of the receiving grid, and it is impossible to direct the beam away from the receiving antenna. Since the receiving grid does not block sunshine, the land beneath can be used for growing farm crops. Microwave intensities reaching the earth are completely safe.

The solar cells in the array are projected to have an 18% efficiency, 2 mil thickness, and cost \$0.28 per cm^2, which should lead to a 430 W/lb array costing \$0.68 per cm^2 and having a 30 year life. The array is expected to suffer a 1% loss of solar cells from micrometoroid impacts over a 30 year period. Glaser[125] gives the cost of a small several hundred megawatt prototype plant, based on current shuttle cost estimates and near-term solar cell

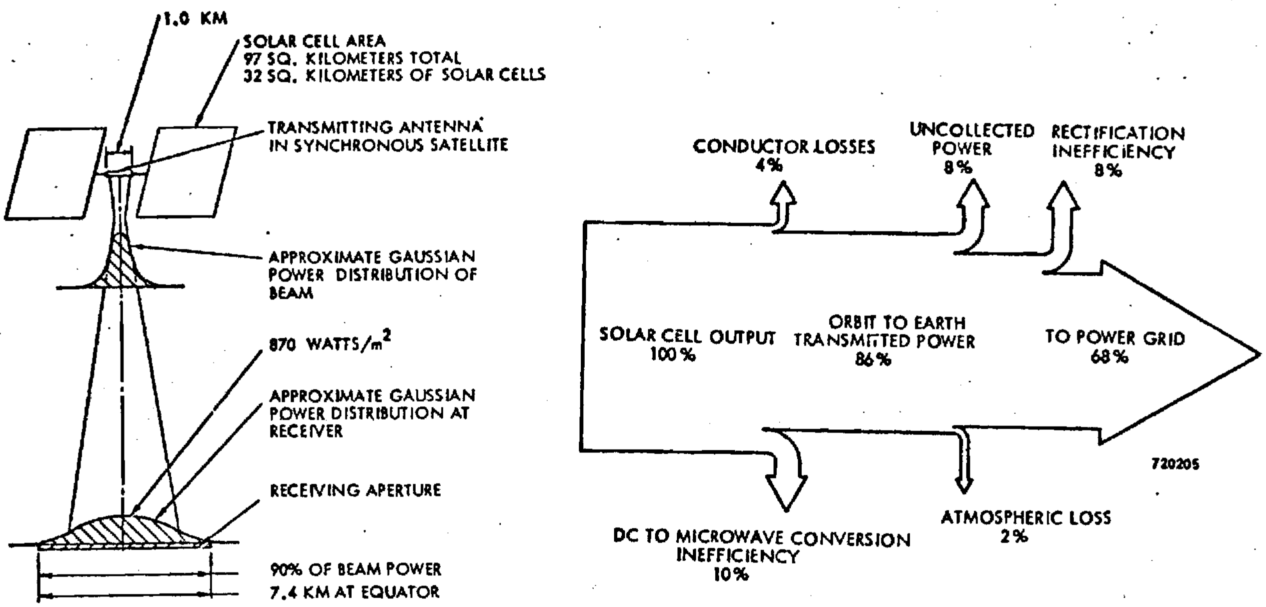


Figure 49. Microwave Transmission to Earth [126]

technology, as \$310/KWe for the solar arrays, \$230/KWe for the microwave transmission system, and from \$800/KWe to \$1380/KWe for transportation to geosynchronous orbit and assembly, for a total system cost of from \$1340/KWe to \$1920/KWe. Capital cost for a fully operational 5000 MWe plant is expected to be about \$800/KWe. The power satellite will produce more energy in its first year of operation than was required to manufacture it and place it in orbit.

Patha and Woodcock [127] explored the feasibility of large geosynchronous solar-thermal plants (Figure 50) operating with a "current technology" helium/xenon brayton cycle, and estimated the capital cost of a 1980 technology plant at \$2540/KWe. Since about 80% of this cost is space transportation, this cost should be reduced if a fully reusable space shuttle becomes operational and lighter weight reflecting surfaces become available. They also projected an advanced solar cell system to cost \$2950/KWe, slightly more than the solar-thermal system. Brown [128] projected the capital cost of solar cell geosynchronous plants to lie in the range of \$1400/KWe to \$2600/KWe. Mockovciak [129] reported

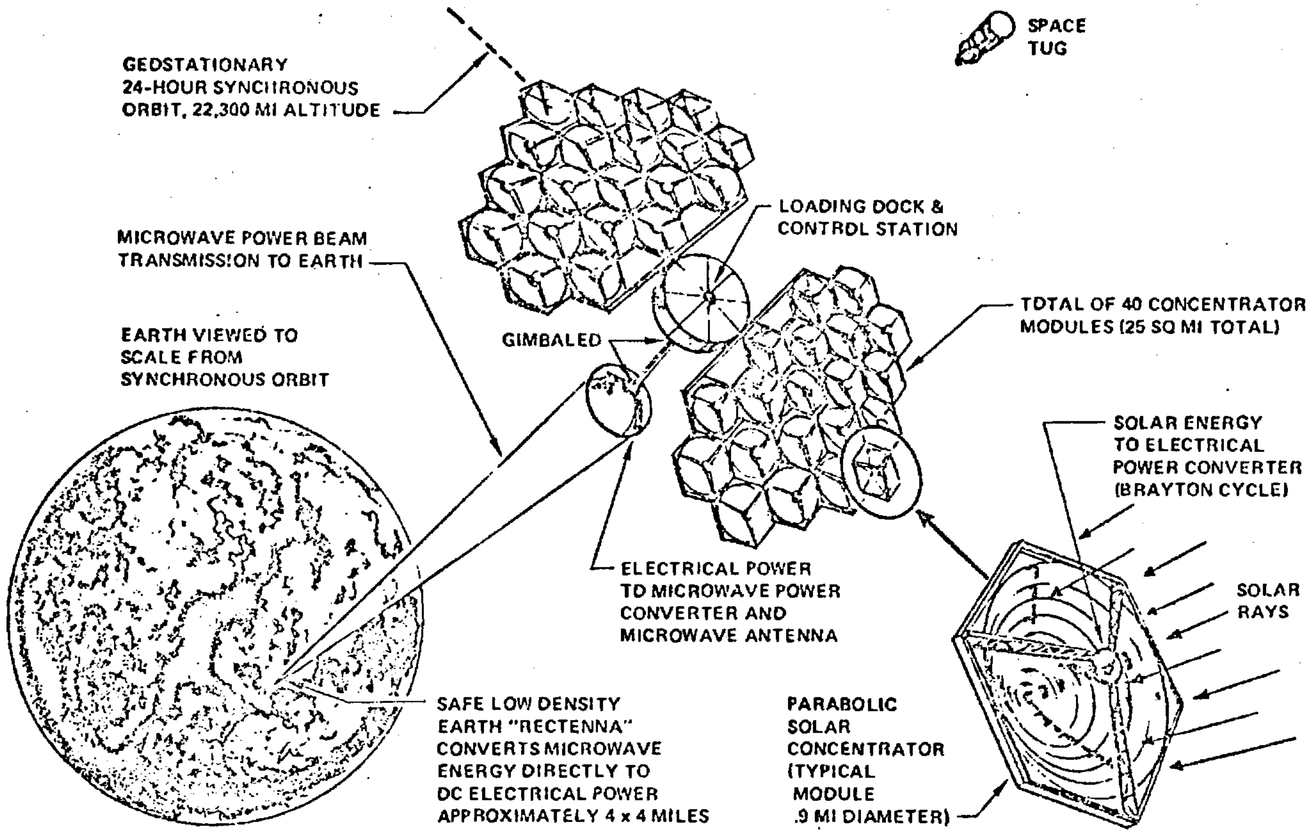


Figure 50. Geosynchronous Solar-Thermal Power Plant

an earlier estimate of $2100/KWe for a protype solar cell plant based on a study by the A.D. Little/Grumman/Raytheon/Textron team. This group has been conducting a study of the solar cell system for several years.

RECOMMENDATIONS AND PROJECTIONS

Figure 51 illustrates the energy flow pattern that occurred in 1970, and the energy flow pattern for 1985 projected by the Joint Committee on Atomic Energy [130]. Oil imports were projected to increase from 3.5 million barrels/day to 14.6 million barrels/day by 1985, and natural gas imports were projected to increase by a factor of 6. Since these projections were made, foreign oil prices have increased as much as a factor of 5, and the Arab embargo has cut foreign oil imports almost in half. Even if the embargo ends, the high price of foreign oil (over $11/barrel) will make the projected imports economically unfeasible. At current prices the projected imports would cost over $60 billion in 1985 alone.

In view of the economic and political realities now facing this country, the President has declared a national goal of "energy sufficiency by 1980." If the United States is to become self sufficient in its energy resources by 1980, or even a few years thereafter, new domestic energy sources must be rapidly developed. Solar energy represents a virtually untapped domestic energy resource which can be very rapidly utilized to reduce fossil fuel requirements.

Solar energy should be developed and used as rapidly as possible, so the following recommendations are made for research, development and demonstration programs in solar heating and cooling, solar electric power generation, and the development of clean, renewable fuels. Wind, ocean currents, and flowing rivers are not included in this study. The following recommendations are listed under the major headings of RESEARCH - highest priority research programs, DEVELOPMENT - development of manufacturing techniques for economically mass producing devices already existing in the laboratory, DEMONSTRATION (3 years) - large scale system demonstrations

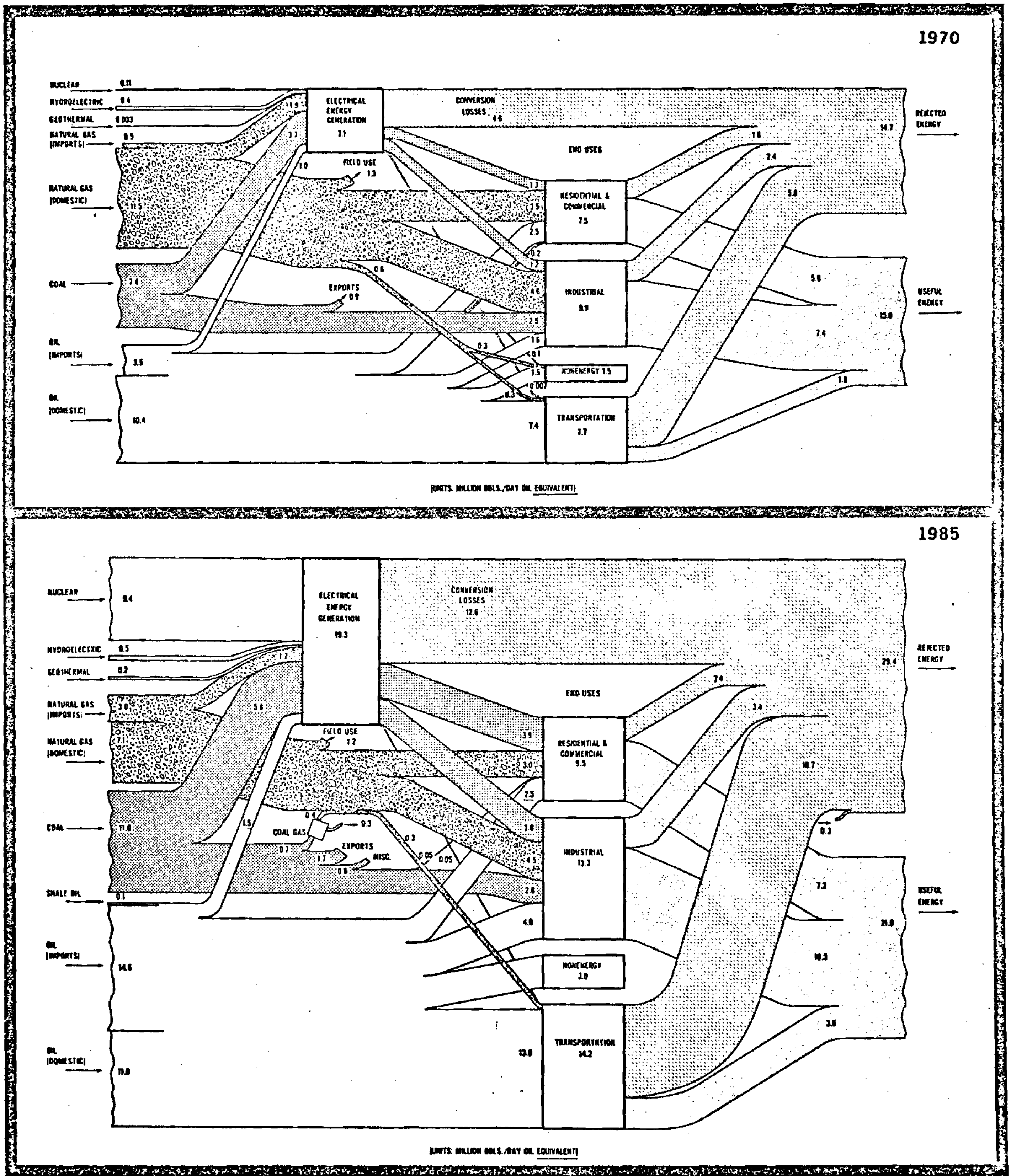


Figure 51. Energy Flow Patterns 1970/1985 130

within 3 years, DEMONSTRATION (8 years) - system studies now, then design, then demonstration within eight years, and DEMONSTRATION (15 years) - systems requiring as much as 15 years to demonstrate if work begins now. All recommendations require immediate action if the systems and devices are to be available in the time frame indicated. They are listed under each heading in order of priority.

Recommendations

RESEARCH

1. Inexpensive, strong, long-lasting, transparent and reflective plastic films should be developed as rapidly as possible. This technology would greatly improve the economics of a variety of solar energy systems.
2. Long-life, cheap, rugged, reasonably efficient solar cells which can be easily assembled into arrays and which will operate at moderately high temperatures (250°F). Major efforts should be devoted to developing new types of solar cells and improving their performance.
3. Plants with high capture efficiency for converting sunlight into biomass require intensive study to improve the performance of bioconversion systems.
4. Low cost compact heat storage systems should be developed to improve the performance of solar heating, cooling and thermal power systems, especially phase-change systems.
5. Heat transport devices for collecting and distributing heat cheaply with minimal loss, including heat pipes.

DEVELOPMENT

1. Mass produced cheap solar cells. The highest priority development effort should be the rapid implementation of large scale manufacturing techniques to produce cheap solar cells, using silicon ribbon or sheets [71-74].
2. Mass produced, cheap optical coatingsfor glass, plastic films,or other materials should be manufactured as soon as possible. These include coatings to increase transmission and coatings to retard infrared emission.
3. Inexpensive, mass produced, durable flat plate collectors, to be made generally available as soon as possible for heating, air conditioning, and water heating. A 4x8 foot collector (without insulation) should cost from \$20 to \$40, and be easily installed with plastic pipe.
4. Economical absorption air conditioning systems made to operate on hot water from a solar collector should be put on the market. The system should be able to use an auxiliary energy source.
5. Cheap, mass produced tracking devicessuch as thermal heliotrops, heliostats, and transistorized sun-sensing mechanisms, are needed for solar concentrator systems.

DEMONSTRATION (3 years)

1. Large-scale solar heating and cooling and hot water for homes, apartments, and other buildings using water cooled flat plate collectors, absorption air conditioning, and hot water storage. With federal support these systems could be installed for demonstration purposes throughout the nation in new apartment complexes, subdivisions, etc.. Collectors can also be installed on vertical walls of tall buildings. Collectors should be blended into the building structure in an attractive manner. The purpose of these demonstrations is to prove the economics and acceptability of these systems at various locations throughout the nation.

2. <u>Substation - sized thermal electric power plants</u> which also supply heat, as required, in the form of steam, hot water, or hot air could be built using the more promising concepts for solar-thermal power generation. Hopefully one or more of these plants will be shown to be economically competitive with alternative power sources.

3. <u>High temperature heat supply systems</u> using solar concentrators and a suitable storage system to provide heat for industrial processes are needed. An example would be a six million BTU/hour 400°F hot air supply system for textile drying operations.

4. <u>Clean, renewable fuels</u> (oil and gas) could be produced from organic materials on a small scale to provide badly needed data relating to the feasibility of future large scale production of these fuels.

5. <u>Low-cost single-story housing with roof panels</u> for heating and cooling can be built in sunny areas to demonstrate the economic feasibility of low income housing of this type in sunny areas.

DEMONSTRATION (8 years)

1. <u>Solar cell flat plate collector</u> electric power, heating and cooling systems for homes, businesses, and even tall buildings. All major system components should be mass manufactured with high reliability long life, minimal maintanence and low cost. Compact low cost heat storage should be included. For tall buildings the collectors can be mounted on vertical walls. Solar total energy systems using integrated collectors should be demonstrated with a variety of building types at various locations around the country. Au iliary fuel requirements should be minimized.

2. <u>One or more prototype ocean thermal power plants</u> producing at least 100 MWe plus fresh water should be built, using different cycles, to establish the feasibility of ocean thermal plants and determine which system performs best.

3. A solar thermal electric power plant of 100 MWe or more should be built in a sunny climate. If two or more proposed plant systems are judged equally promising, each should be built. These prototype plants should determine whether or not large scale solar thermal conversion is practical.
4. Prototype clean renewable fuel plants of several types should be built. At least one of these organic conversion plants should process municipal wastes, one receive wastes from a large feedlot, and one or more process plant matter grown specifically for the bioconversionfacility. Cheap, automated techniques for harvesting the plants and transporting the materials to the bioconversion facility, should be developed and used. The primary purpose of these projects should be to demonstrate the economic feasibility of large-scale operations.
5. An energy plantation power plant of at least several hundred MWe utilizing minimum cost harvesting and transportating techniques should be built.

DEMONSTRATION (15 years)

1. Economical, attractive, long-life, low maintanence total energy systems for residences and buildings with long term storage for fuel or electric power produced by the system, automobiles powered by this fuel or electricity, and recycling of liquid wastes should be developed. The objective would be to demonstrate a system which could become standard for new structures built in the 1990's and beyond.
2. Large scale production of renewable fuels (hydrogen, methane, oils) aimed at virtually elliminating the burning of fossil fuels,which can be better used by the chemical industry,should be pursued.
3. A prototype geosynchronous solar power plant of about 1000 MWe or more using the space shuttle and microwave transmission should be built, if the required technologies are developed by that time.

4. Large scale terrestrial electric power plants of more than 1000 MWe could be built if the economics are proven by the prototypes or solar cell arrays are manufactured very cheaply.

5. An ocean-thermal sea plant producing power, fresh water, chemicals, fertilizers, and minerals should be built with government support if a prototype is successful.

Although the recommendations in each category are listed in order of priority, the development of all these systems should be pursued with vigor. It is recommended also that the government pay the entire cost of the demonstration projects, and then after the plants are built and tested, sell them on an open bid basis. To promote the widespread use of systems which are developed and demonstrated, the government should provide tax credits for the installation of solar energy systems, since they do not deplete nonrenewable resources. An alternative approach is to tax resource depletion and pollution associated with the use of fossil and nuclear fuels.

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E-25-633 / E-26-606

FINAL REPORT

NASA Grant NGR-11-002-166

COMPARATIVE EVALUATION OF SOLAR, FISSION, FUSION, AND FOSSIL ENERGY RESOURCES

PART II

POWER FROM NUCLEAR FISSION

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ACKNOWLEDGMENT

The permission of the Nuclear Assurance Corporation to reproduce graphs from its Fuel-trac service (references 5 and 6) for use in this report is gratefully acknowledged.

POWER PRODUCED BY NUCLEAR FISSION REACTORS

INTRODUCTION

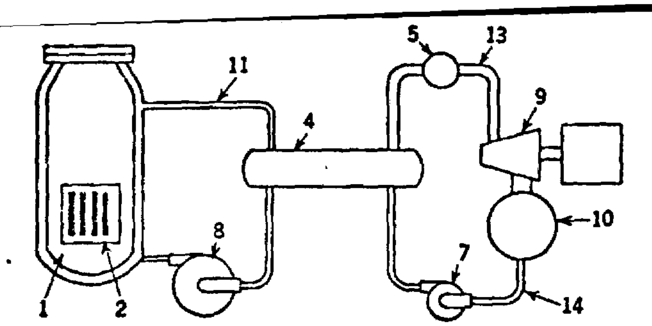
Nuclear power is now (1974) producing approximately 5% of the electrical power in the United States. It has been estimated that by the year 2000 power from nuclear energy will equal or exceed that produced by fossil sources. It appears that the recent crisis in energy and oil has led to a series of events which will speed up dramatically the role of nuclear power in the United States.

It is well known that the fissile nulcear fuels are: uranium-235, which composes 0.7% of natural uranium, the odd isotopes (Pu-239 and Pu-241) of plutonium which are produced by the neutron irradiation of the fertile U-238, and U-233 which is produced by the neutron irradiation of thorium as found in nature. The present generation of power reactors in the United States are mostly light water reactor (LWR) moderated and cooled, using slightly enriched uranium as uranium dioxide for the fuel. Of the light water reactors, the pressurized water reactor is manufactured by the Westinghouse Electric Corporation, the Babcock and Wilcox Corporation, and the Combustion Engineering Corporation. The boiling water reactor is manufactured by the General Electric Corporation. The Gulf General Atomic Corporation is producing a gas-cooled graphite moderated thermal reactor. The LWR's and HTGR's are converter reactors, that is, the fissile isotopes which are produced in the course of energy production are less than those used up.

Another class of fission reactors which is predicted to become important in approximately the year 2000 is the breeder reactor. In a breeder reactor the fissionable material which is produced is in excess of that which is utilized for the energy production. For example, in a neutron irradiation of U-238 more plutonium could be produced than uranium consumed. There are two important candidates for breeders which shall be considered later, namely the liquid/metal cooled fast breeder reactor (LMFBR) and the gas cooled fast breeder reactor (GCFBR). Figure 1 (taken from reference 1) indicates the four most important reactor systems under consideration.

Some of the important differences between nuclear fuels and fossile fuels are as follows:

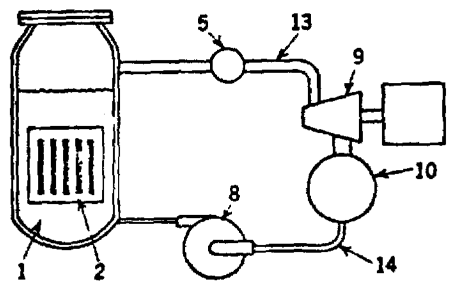
1. Nuclear fuels, as compared to fossile fuels, are fabricated in a chain of development processes which encompass a large high technology nuclear fuels industry, and involves a complex fuel cycle.
2. The procurement of nuclear fuels requires very long lead times. In order to procure a core loading, orders for nuclear fuels must be made several years before the fuels are in the reactor.
3. Nuclear fuels are costly and require a large initial investment many months before use. As a result, one must consider carrying charges as an important factor in computing the nuclear fuel costs.
4. Another difference between the nuclear fuels and fossil fuels is that the irradiated reactor fuel when taken out of the reactor has a high residual value. This is a consequence, of course, of the fact that all of the Uranium-235 or fissile fuel is not burned up in the reactor and also the fact that plutonium may be produced by the irradiation of the U-238. Hence, the high residual value of the fuel requires a reprocessing operation and a storage operation which must be considered in fuel cycle cost calculations.
5. The irradiated fuel discharged from the reactor is radioactive and



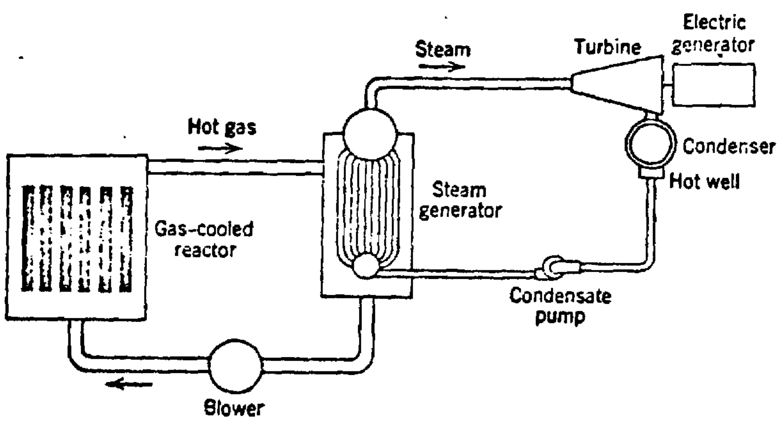
Legend*:

1 Reactor
2 Core
3 Blanket
4 Boiler
5 Steam drier
6 Intermediate heat exchanger
7 Feed water pump
8 Circulating pump
9 Turbogenerator
10 Condenser
11 Primary coolant
12 Intermediate coolant
13 Steam
14 Condensate

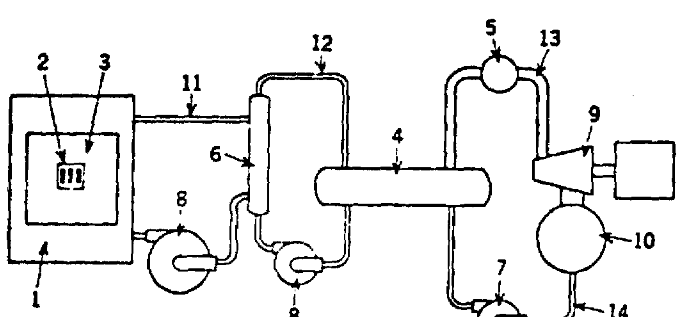
Pressurized-water reactor system.



Direct-cycle boiling-water reactor.



Gas-cooled reactor system for steam generation.



Fast-breeder reactor system.

Figure 1. Diagrams of Reactor System[1]

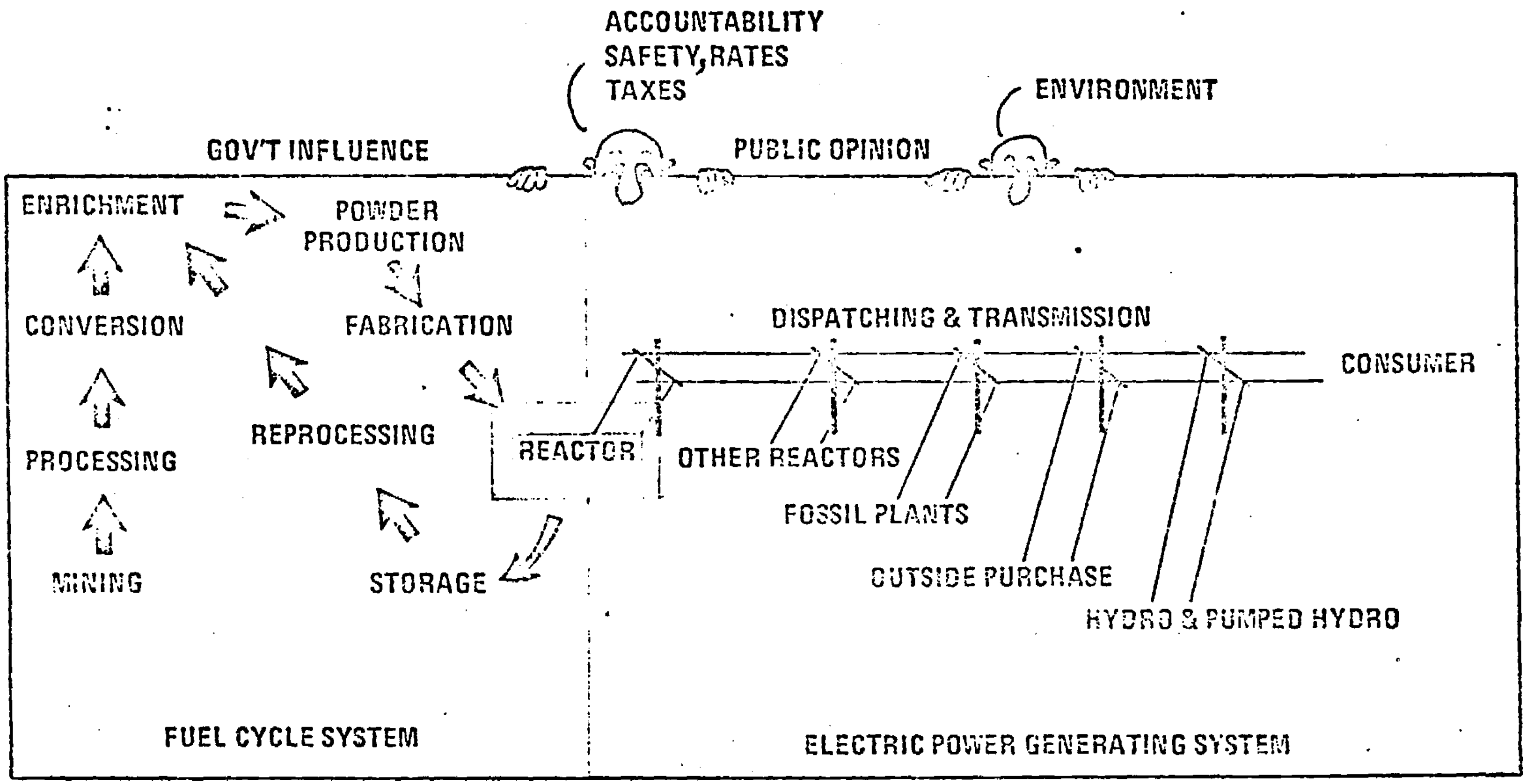
poses a problem of storing for a time interval before the fuel can be shipped. It also entails a very difficult problem for the ultimate disposal of the nuclear wastes.

THE REACTOR AS A COMPONENT IN THE FUEL AND THE POWER SYSTEMS

In understanding the role of a nuclear fission reactor in the production of nuclear power it is convenient to consider the reactor as a component in the fuel cycle system and also as a component in the power system. The cost of power produced by the nuclear reactors is strongly influenced by its utilization as a component in the power system.[2,3]

Figure 2 illustrates the viewpoint of considering a reactor as a component in two complex systems. Notice that, in looking at the left hand side of Figure 2, one notes that the reactor is a component in the fuel cycle. In this system, the fuel is obtained from the mine, the raw ore is used in a processing operation to produce yellowcake U_3O_8. The U_3O_8 is converted to uranium hexaflouride in conversion operation, followed by the enrichment operation in which the U-235 isotopic concentration is enhanced. After the enriched uranium dioxide powder is produced, fuel elements are produced which after a series of operations are put into a form of fabricated fuel assemblies for insertion into the reactor. The spent fuel from the reactor is stored for cooling and reprocessed to obtain the remaining U-235 and any plutonium which has been produced. The extracted U-235 can in turn be reenriched and continued through the cycle and the plutonium can be extracted and used in plutonium recycle.

Figure 3 is a more detailed diagram of the fuel cycle, also depicting the thorium cycle and plutonium recycle. The right-hand side of the figure indicates the reactor as a component in the power system. The production of power by the reactor is used to satisfy the demand as set by the consumer. The utility has the option of meeting the consumer demands by committing and dispatching other electrical power generating equipment in the power system. These include fossil plants, possibly other reactors, hydraulic and



OVERALL SYSTEM

Figure 2. The Reactor as a Component in the Fuel System and the Power System

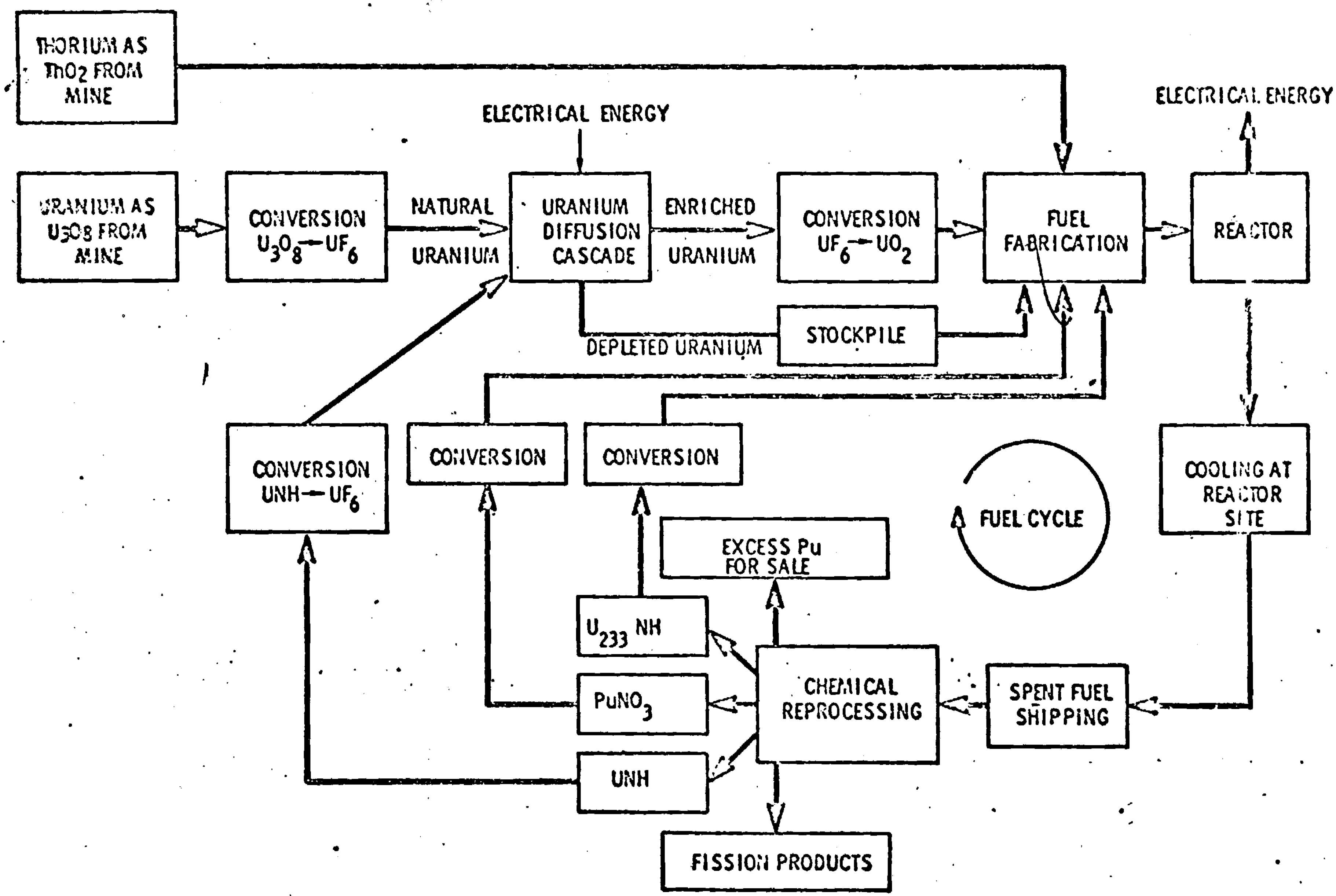


Figure 3. The Nuclear Fuel Cycle

pumped hydraulic plants which may be available. Energy can also be purchased from an outside neighboring utility. The decision of unit commitment and dispatching requires an economic optimization which may be influenced by obviously the demand but also such other government influences as safety, rates, taxes, from the environment, from public opinion. According to Hoskins[3]

> "Early in the development of nuclear power it was recognized that the operating constraints and economic considerations in the operation of nuclear units on a power system are quite different than for conventional fossil-fueled generating units. In the past, economic optimization of power system operation has, for the most part, been based primarily on incremental generating cost from fossil units, which is essentially a function of instantaneous fuel cost and variation of heat rate with plant operating level. With the large scale introduction of commercial nuclear power plants it became increasingly apparent that traditional methods are inadequate for planning the operation of power system operation. This is due to the complex nature of the fuel cycle, fuel cycle economics and constraint imposed incore fuel management. If utilities are to effectively utilize nuclear units, new power system operational methods must be developed which encompass the ability to manage nuclear fuel from an overall power system viewpoint. Such power systems include various combinations of nuclear plants, fossil fuel fired plants, gas turbine peaking plants, conventional, and pumped-storage plants."

UNITED STATES ENERGY CONSUMPTION BY SOURCE
1971 - 2000
(QUADRILLION BTU's)

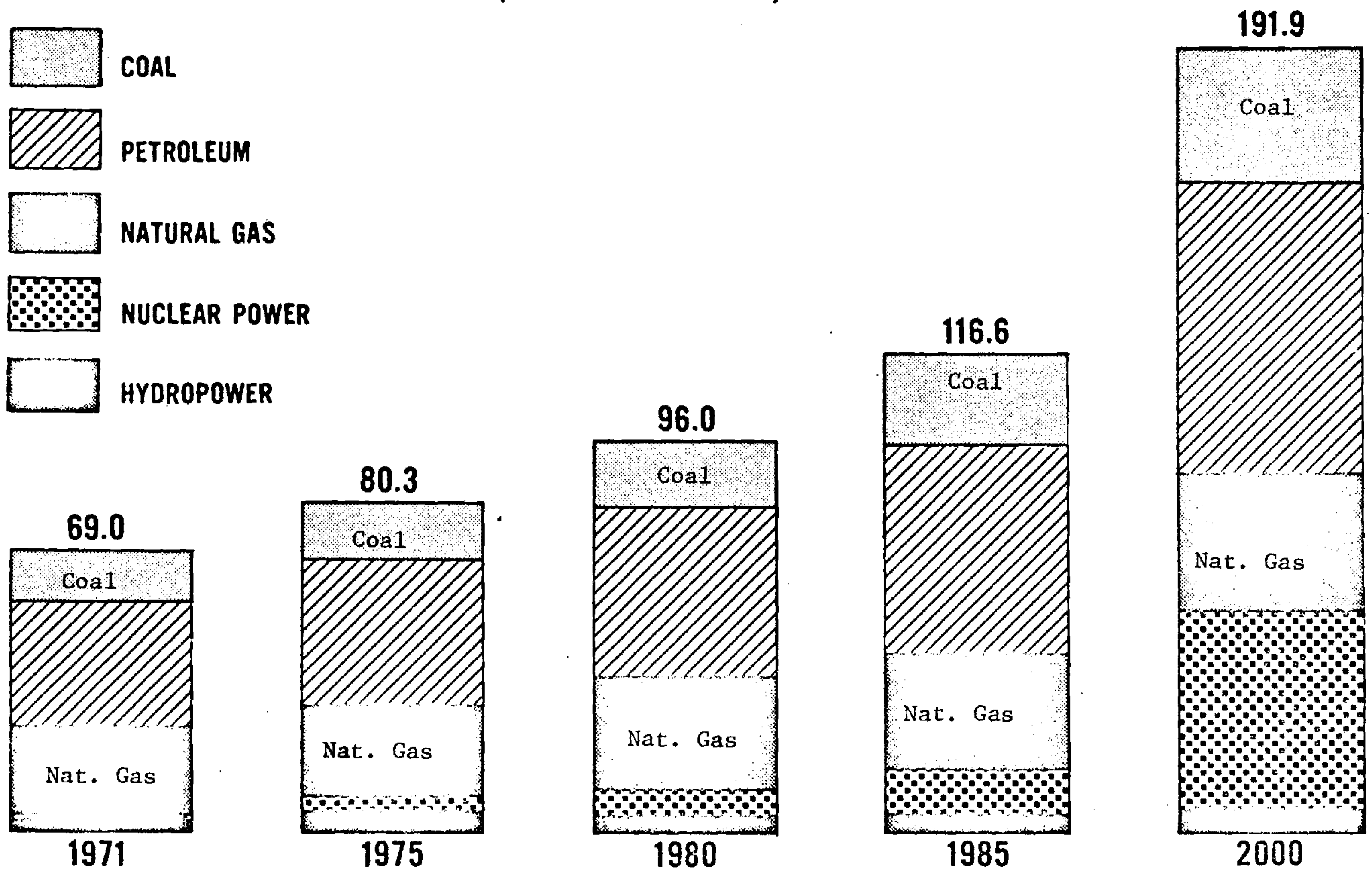


Figure 4[4]

NUCLEAR POWER STATUS AND PROJECTIONS

There are a large number of projections for the production of electrical power by various kinds of power sources. Although some of the projections are not in exact agreement, all of the projections indicate that nuclear power will provide a significant supply of the electrical power in the United States by the year 2000. For example, Figure 4 (Reference 4) indicates that by the year 2000 electrical power production from nuclear sources will be equal to about 160% of the power provided by coal. Table 1 taken from Reference 4 is an estimate provided by the Department of Interior which predicts that by the year 2000 nuclear power will provide 49,230 x 10^{12} BTU's as compared with coal which provides 31,360 x 10^{12} BTU's.

TABLE 1

Energy Source	1971[1]	1975	1980	1985	2000
Coal	12,560	13,825	16,140	21,470	31,360
Petroleum	30,492	35,090	42,190	50,700	71,380
Natural Gas	22,734	25,220	26,980	28,390	33,980
Nuclear Power	405	2,560	6,720	11,750	49,230
Hydropower	2,798	3,570	3,990	4,320	5,950
Total	68,989	80,265	96,020	116,630	191,900

(All figures in trillions of BTU)

1 Actual

Most estimates, including those in Table 1, were made before the oil crisis of the past few months. Undoubtedly the role of nuclear power will be enhanced as a result of actions taken by the United State Government. One whould look also toward other possible sources such as solar and geothermal.

To provide the most authoritive data on the exact present status and firmly committed development of nuclear power in the United States, the Nuclear Assurance Corporation of Atlanta has a data bank encompassing firm committments and also predictions as indicated by the Futura program through the year 1981. Authors of this report wish to thank the Nuclear Assurance Corporation for their permission to include in this section the results of their Fuel-Tract and Futura services.

Following are quotations and figures from References 5 and 6.

"This Nuclear Fuel Status and Forecast section of the fuel-trac Quarterly Report is concerned with the current and projected requirements for materials and services throughout the fuel cycle.

The information contained herein is unique to fuel-trac since it it is based upon the operating and fuel management plans of the individual utilities and not upon average quantity assumptions and projections. Fuel-trac assumptions are incorporated into the system only for those powerplants that are anticipated but not yet ordered; hence, only for those contemplated plants where no information is available from outside sources. Information on these projected reactors is generally separately shown throughout the report and is indicated as FUTURA.

The fuel cycle requirements (quantity and timing) data are generated within the fuel-trac computer system by modeling of the entire industry and the operations of individual suppliers. Timing of feed materials requirements for a particular step in the fuel cycle is therefore a function of the individual supplier's plant capacity and his commitments at that time. Also, his feed materials requirements for a specific product output include processing losses which are incorporated into the fuel-trac computer system through analysis of historical information.

Commitments information is obtained from both the electric utilities and their contractors. The quantities ordered at any particular time, for example U_3O_8, may not be exactly identical to the quantities required to fuel a specific reactor and/or may include requirements for more than one reactor. The fuel-trac computer system prorates the ordered quantities according to requirements and thereby ascertains a true picture of requirements not committed or excesses purchased.

In general this Quarterly Report provides an industry summary picture that is built up from the detailed requirements and commitments status of each utility and supplier."[5,6]

GLOSSARY OF U.S.A. PRODUCTION FACILITIES

URANIUM ORE PROCESSING FACILITIES

ıp I.D. # 1 Anaconda Co., Grants, N.M.
2 Atlas Corp., Moab, Utah
3 Cotter Corp., Canon City, Colo.
4 Dawn Mining Co., Ford, Wash.
5 Federal-American Partners, Gas Hills, Wyo.
6 Kerr-McGee Corp., Grants, N.M.
8 Petrotomics Co., Shirley Basin, Wyo.
12 Union Carbide Corp., Gas Hills, Wyo.
13 Union Carbide Corp., Uravan, Colo.
14 United Nuclear-Homestake Partners, Grants, N.M.
15 Utah International, Inc., Gas Hills, Wyo.
16 Utah International, Inc., Shirley Basin, Wyo.
17 Western Nuclear Corp., Jeffrey City, Wyo.
18 Continental Oil – Pioneer Nuclear, Falls City, Texas
19 Exxon Co., U.S.A., Douglas, Wyo.
20 Rio Algom Corp., La Sal, Utah

U_3O_8 – UF_6 CONVERSION FACILITIES

ap I.D. # 1 Allied Chemical Corp., Metropolis, Ill.
2 Kerr-McGee Corp., Sallisaw, Okla.

SPENT FUEL REPROCESSING FACILITIES

ıp I.D. # 1 Nuclear Fuel Services, Inc., West Valley, N.Y.
2 General Electric Co., Morris, Ill.
3 Allied-Gulf Nuclear Services, Barnwell, S.C.

ZIRCONIUM METAL PROCESSING FACILITIES

Map I.D. # 1 General Electric Co., Wilmington, N.C.
2 Sandvik Special Metals Co., Kennewick, Wash.
3 Westinghouse Electric Corp., Blairsville, Penn.
4 Wolverine Tube, Allen Park, Mich.
5 Zirconium Technology Corp., Albany, Ore.
6 AMAX Specialty Metals, Inc., Akron, N.Y.
7 Teledyne Wah Chang Albany Corp., Albany, Ore.

URANIUM ENRICHMENT FACILITIES

Map I.D. # 1 USAEC, Oak Ridge, Tenn.
2 USAEC, Paducah, Ky.
3 USAEC, Portsmouth, Ohio

UO_2 FUEL FABRICATION FACILITIES

Map I.D. # 1 Babcock & Wilcox Co., Lynchburg, Va.
2 Combustion Engineering, Inc., Windsor, Conn.
3 General Electric Co., Wilmington, N.C.
4 Exxon Nuclear Co., Inc., Richland, Wash.
5 NUMEC Division - Babcock & Wilcox Co., Apollo, .
6 Gulf United Nuclear Fuels Corp., New Haven, Conn.
7 Westinghouse Electric Corp., Columbia, S.C.
9 Kerr-McGee Corp., Cimarron, Okla.
10 Nuclear Fuel Services, Inc., Erwin, Tenn.
11 Gulf United Nuclear Fuels Corp., Hematite, Mo.
12 Nuclear Fuel Services, Inc., West Valley, N.Y.
13 Gulf General Atomic Co., San Diego, Calif.

GLOSSARY OF EUROPEAN PRODUCTION FACILITIES

URANIUM ORE PROCESSING FACILITIES

1. CEA, Gueugnon, France
2. SIMO (Society Industrielle des Minerais de l'Quest), Ecarpiere, France
3. SIMO (Society Industrielle des Minerais de l'Quest), Bessines, France
4. SIMO (Society Industrielle des Minerais de l'Quest), Forez, France
5. Junta de Energia Nuclear, Andujar, Spain
6. Junta de Energia Nuclear, Salamanca, Spain
7. A B Atomenergi, Rantstad, Sweden
8. Versuchsanlage fuer Uranerz der Gewerkschaft Brunhilde-Ellweiler, Federal Republic of Germany
9. Junta de Energia Nuclear, Urgeirica, Portugal

U_3O_8 – UF_6 CONVERSION FACILITIES

1. COMURHEX (Societe pour la Conversion de l'Uranium en Metal et en Hexafluoure), Pierrelatte, France
2. BNFL (British Nuclear Fuels Limited), Springfields, Lancashire, UK

POWER GENERATION

OPERATING POWER PLANTS

Name	Utility	NSSS Vendor	Net MWe	Commercial Operation Date
U.S.A.				
Dresden – Unit 1	Commonwealth Edison Company	GE	200	August 1960
Yankee – Unit 1	Yankee Atomic Electric Company	West.	175	February 1961
Indian Point – Unit 1	Consolidated Edison Co. of N.Y.	B&W	275	December 1962
Big Rock Point	Consumers Power Co.	GE	72	January 1963
Connecticut Yankee	Connecticut Yankee Atomic Power Company	West.	575	January 1968
San Onofre – Unit 1	Southern California Edison Co.	West.	425	January 1968
R. E. Ginna	Rochester Gas & Electric Company	West.	500	December 1969
Oyster Creek – Unit 1	Jersey Central Power & Light	GE	650	January 1970
Nine Mile Point – Unit 1	Niagara Mohawk Power Company	GE	625	January 1970
Dresden – Unit 2	Commonwealth Edison Company	GE	800	July 1970
Point Beach – Unit 1	Wisconsin Electric Power Company	West.	500	December 1970
Millstone – Unit 1	Millstone Point Co.	GE	650	December 1970
Oconee Nuclear Station – Unit 1	Duke Power Company	B&W	875	August 1973
Robinson – Unit 2	Carolina Power & Light	West.	700	March 1971
Monticello	Northern States Power Company	GE	550	July 1971
Dresden – Unit 3	Commonwealth Edison Company	GE	800	September 1971
Palisades	Consumers Power Co.	C-E	700	July 1972
Quad Cities – Unit 1	Commonwealth Edison Company	GE	1050	July 1972
Quad Cities – Unit 2	Commonwealth Edison Company	GE	1050	August 1972
Point Beach – Unit 2	Wisconsin Electric Power Company	West.	500	October 1972
Surry – Unit 1	Virginia Electric & Power Company	West.	900	December 1972
Turkey Point – Unit 3	Florida Power & Light	West.	700	December 1972
Turkey Point – Unit 4	Florida Power & Light	West.	700	July 1973
Maine Yankee	Maine Yankee Atomic Power Co.	C-E	800	December 1972
Vermont Yankee	Vermont Yankee Nuclear Power Corp.	GE	825	December 1972
Pilgrim – Unit 1	Boston Edison Company	GE	650	December 1972
Surry – Unit 2	Virginia Electric & Power Company	West.	900	March 1973
Oconee – Unit 1	Duke Power Company	B&W	875	June 1973

ABBREVIATIONS

(U.S.A.)

SUPPLIERS, ENGINEERS, CONSTRUCTORS

B&W	Babcock & Wilcox Company
C-E	Combustion Engineering, Inc.
GE	General Electric Company
GGA	Gulf General Atomic Company
West.	Westinghouse Electric Corporation
AEPSC	AEP Service Corporation
Bechtel	Bechtel Corporation
Brown	Brown & Root, Inc.
B&R	Burns & Roe, Inc.
Daniel	Daniel Construction
Ebasco	Ebasco Services, Inc.
G&H/D&R	Gibbs & Hill/Durham & Richardson
Gilbert	Gilbert Associates, Inc.
Jones	J. A. Jones Construction Company
Kaiser	Kaiser Engineers
Kiewit	Peter Kiewit Sons' Company
Parsons	Ralph M. Parsons Company
Pioneer	Pioneer Services & Engineering
S&L	Sargent & Lundy
S-S	Southern Services
SS/BC	Southern Services/Bechtel Corporation
S-R	Stearns-Roger Corporation
S&W	Stone & Webster Engineering Corporation
UE&C	United Engineers & Constructors, Inc.
Indep.	Independent Constructor
OPS	Offshore Power Systems

NUCLEAR POWER CAPACITY

FIRMLY COMMITTED REACTORS

		Prior to 1972	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Total of Country
U.S.A. &	MWe	7498	6379	8220	14512	13094	6976	11572	7892	18585	26608	24923	146259
Puerto Rico	# of Reactors	15	9	10	18	14	7	12	8	18	24	22	157
Austria	MWe						692						692
	# of Reactors						1						1
Belgium	MWe			390		1260							1650
	# of Reactors			1		2							3
Brazil	MWe							600					600
	# of Reactors							1					1
Federal Republic	MWe	810	1270		1146	1635	4653	864	2485	1260			14123
of Germany	# of Reactors	3	2		1	2	5	1	2	1			17
Finland	MWe						420		1080				1500
	# of Reactors						1		2				3
France	MWe	266				898	898	903	1920	995			5880
	# of Reactors	1				1	1	1	2	1			7
India	MWe	380											380
	# of Reactors	2											2
Italy	MWe	396				800							1196
	# of Reactors	2				1							3
Japan	MWe	1060	470	1160	2041	2570	5333	4912	2779	4740	5521		30586
	# of Reactors	3	1	2	3	4	6	6	3	5	6		39
Mexico	MWe							640					640
	# of Reactors							1					1
Netherlands	MWe			450									450
	# of Reactors			1									1
Republic of China	MWe					604	604		900	900			3008
	# of Reactors					1	1		1	1			4
Republic of Korea	MWe					564							564
	# of Reactors					1							1
Spain	MWe	593					1804	2761	1804				6962
	# of Reactors	2					2	3	2				9
Sweden	MWe	440			2142	580	900	1480	900	900			7342
	# of Reactors	1			3	1	1	2	1	1			10
Switzerland	MWe	350	656						1860	918			3784
	# of Reactors	1	2						2	1			6
Total by Year	MWe	11793	8775	10220	19841	22005	22280	23732	21620	28298	32129	24923	225616
	# of Reactors	30	14	14	25	27	25	27	23	28	30	22	265

NUCLEAR POWER CAPACITY

Firmly Committed and Futura

GRAPH 1

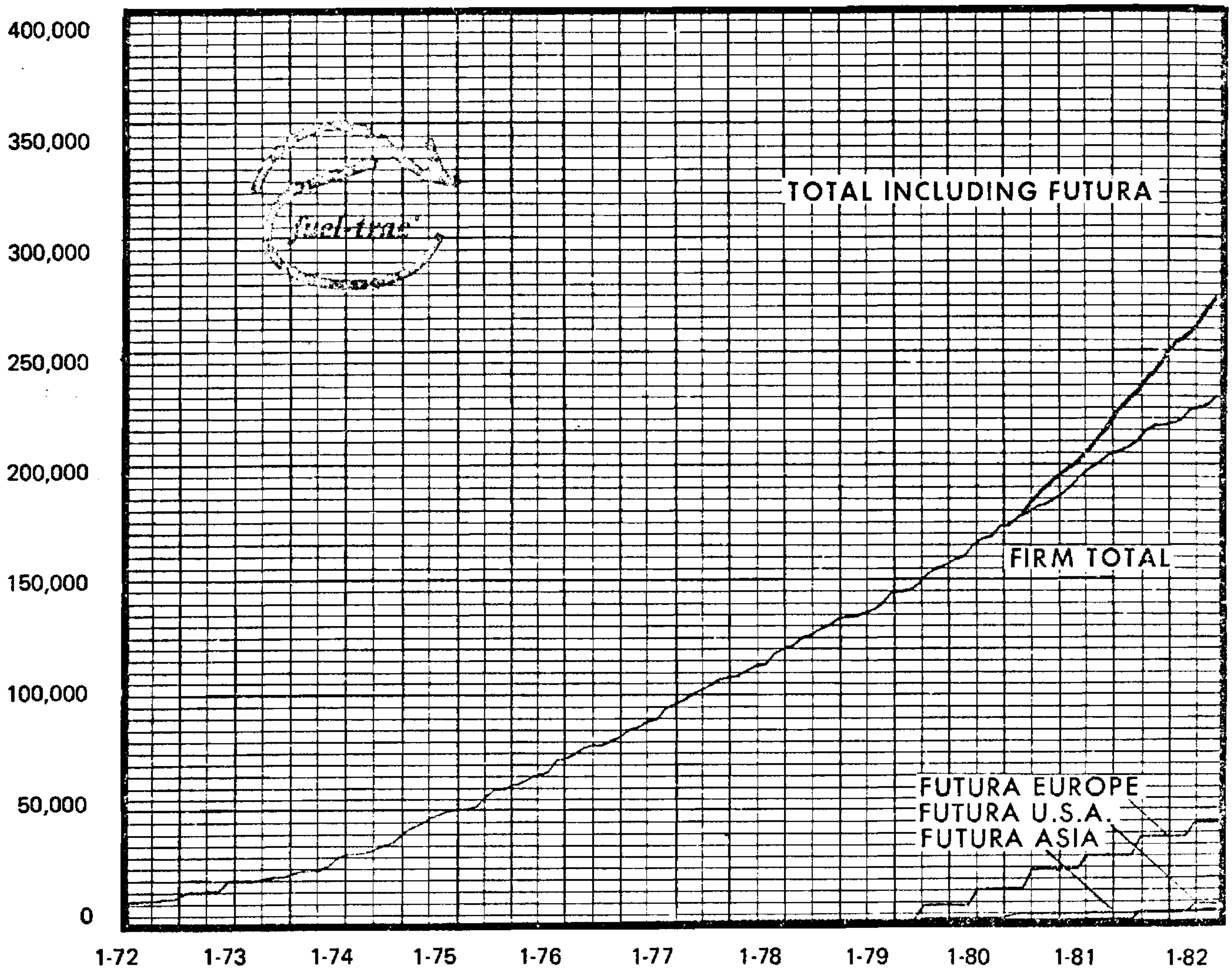


TABLE 3

ANNUAL CAPACITY BREAKDOWN – MWe NET

	1972**	1973	1974	1975	1976	1977	1978	1979	1980	1981
RM TOTAL*	20568	10220	19841	22005	22280	23732	21620	28298	32129	24923
JTURA										
U.S.A.	0	0	0	0	0	0	0	0	0	9943
EUROPE	0	0	0	0	0	0	0	14110	14050	13910
ASIA	0	0	0	0	0	0	0	0	0	6600
JTURA TOTAL	0	0	0	0	0	0	0	14110	14050	30453
RM + FUTURA TOTALS	20568	10220	19841	22005	22280	23732	21620	42408	46179	55376

' Includes Reactors not in U.S.A., Europe and Asia
' Cumulative through 1972

COMMITTED NUCLEAR POWER CAPACITY

Firmly Committed

GRAPH 2

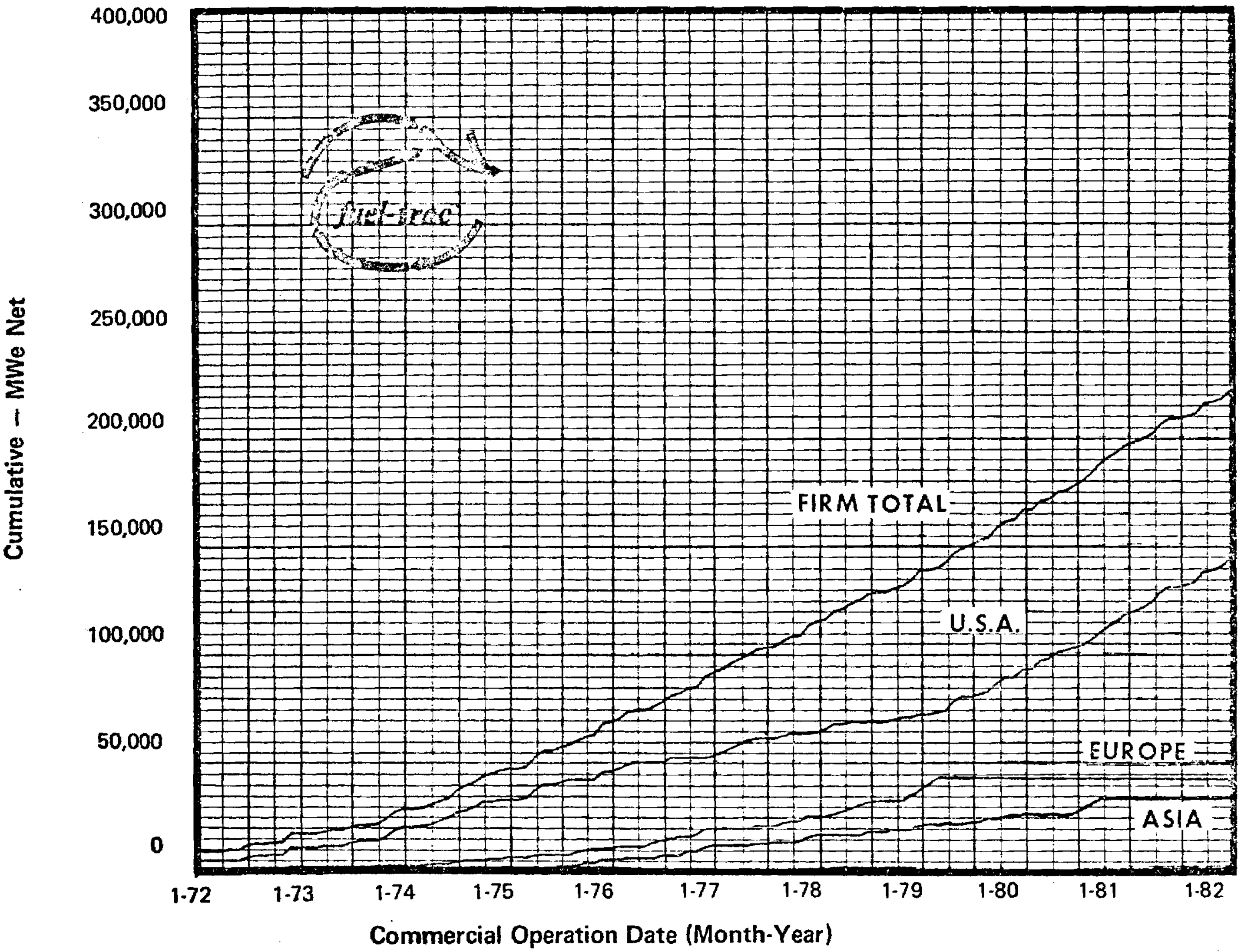


TABLE 4

ANNUAL CAPACITY BREAKDOWN — MWe NET

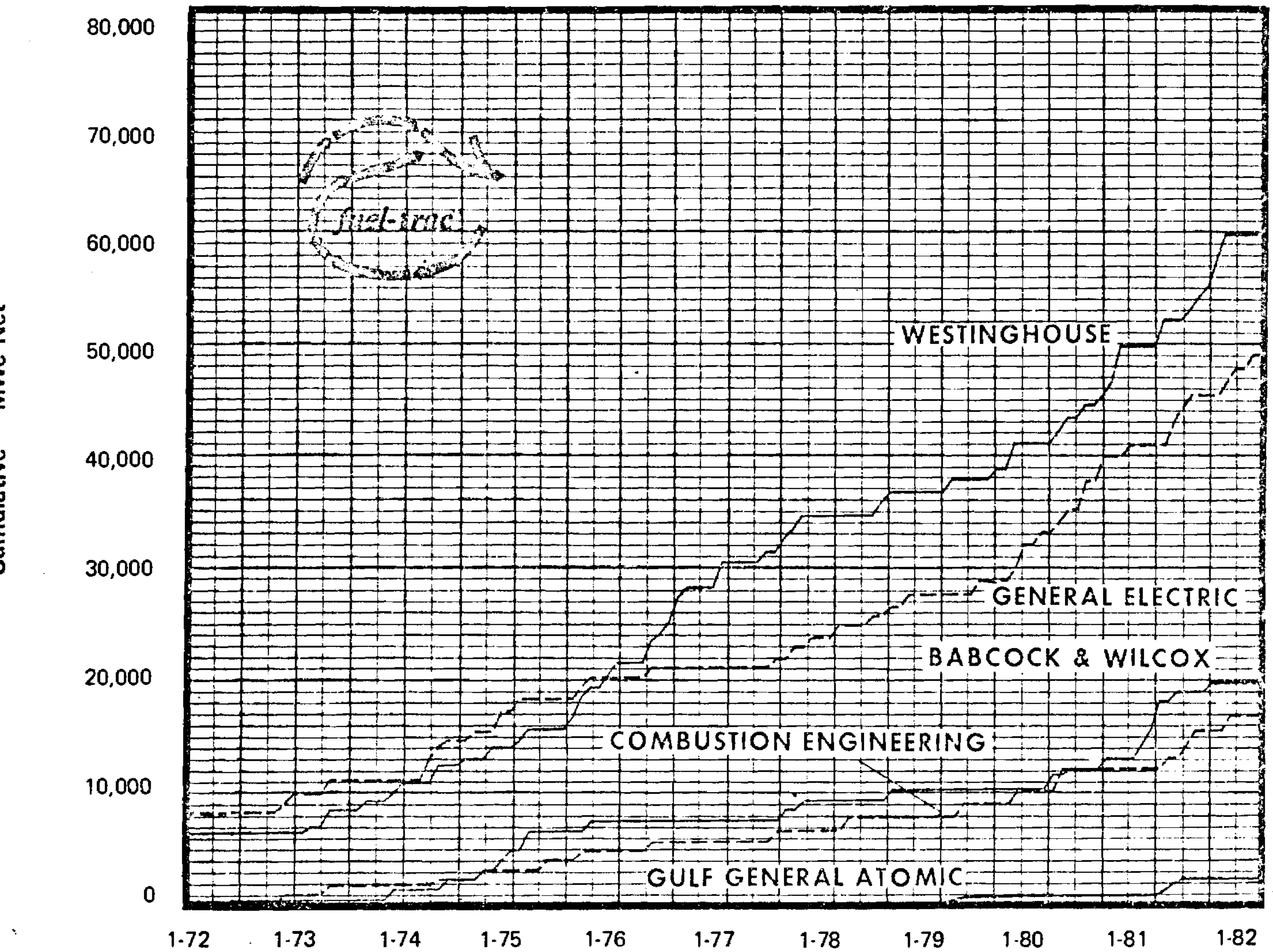
	1972**	1973	1974	1975	1976	1977	1978	1979	1980	1981
U.S.A.	13877	8220	14512	13094	6976	11572	7892	18585	26608	24923
EUROPE	4781	840	3288	5173	9367	6008	10049	4073	0	0
ASIA	1910	1160	2041	3738	5937	4912	3679	5640	5521	0
TOTAL	20568	10220	19841	22005	22280	22492	21620	28298	32129	24923

* Cumulative through 1972

U. S. A. NUCLEAR POWER CAPACITY

Firmly Committed By NSSS

GRAPH 3



Commercial Operation Date (Month-Year)

TABLE 5

ANNUAL CAPACITY BREAKDOWN MWe NET

	1972**	1973	1974	1975	1976	1977	1978	1979	1980	1981
S SUPPLIERS										
BABCOCK & WILCOX	265	886	5153	906	0	1724	893	1763	6785	893
% ANNUAL TOTAL	2	11	36	7	0	15	11	9	25	4
COMBUSTION	1614	457	1628	1601	0	2085	1150	3030	2050	3900
% ANNUAL TOTAL	12	6	11	12	0	18	15	16	8	16
GENERAL ELECTRIC	7153	2943	4237	2706	0	3679	2671	7580	9068	8012
% ANNUAL TOTAL	52	36	29	21	0	32	34	41	34	32
GULF GENERAL ATOMIC	0	0	330	0	0	0	0	770	0	1160
% ANNUAL TOTAL	0	0	2	0	0	0	0	4	0	5
WESTINGHOUSE	4845	3934	3164	7881	6976	4084	3178	5442	8705	10958
% ANNUAL TOTAL	35	48	22	60	100	35	40	29	33	44
TAL ANNUAL CAPACITY	13877	8220	14512	13094	6976	11572	7892	18585	26608	24923

Cumulative through 1972

URANIUM ORE PROCESSING

U.S.A., Europe, Asia

Cumulative Requirements

GRAPH 4

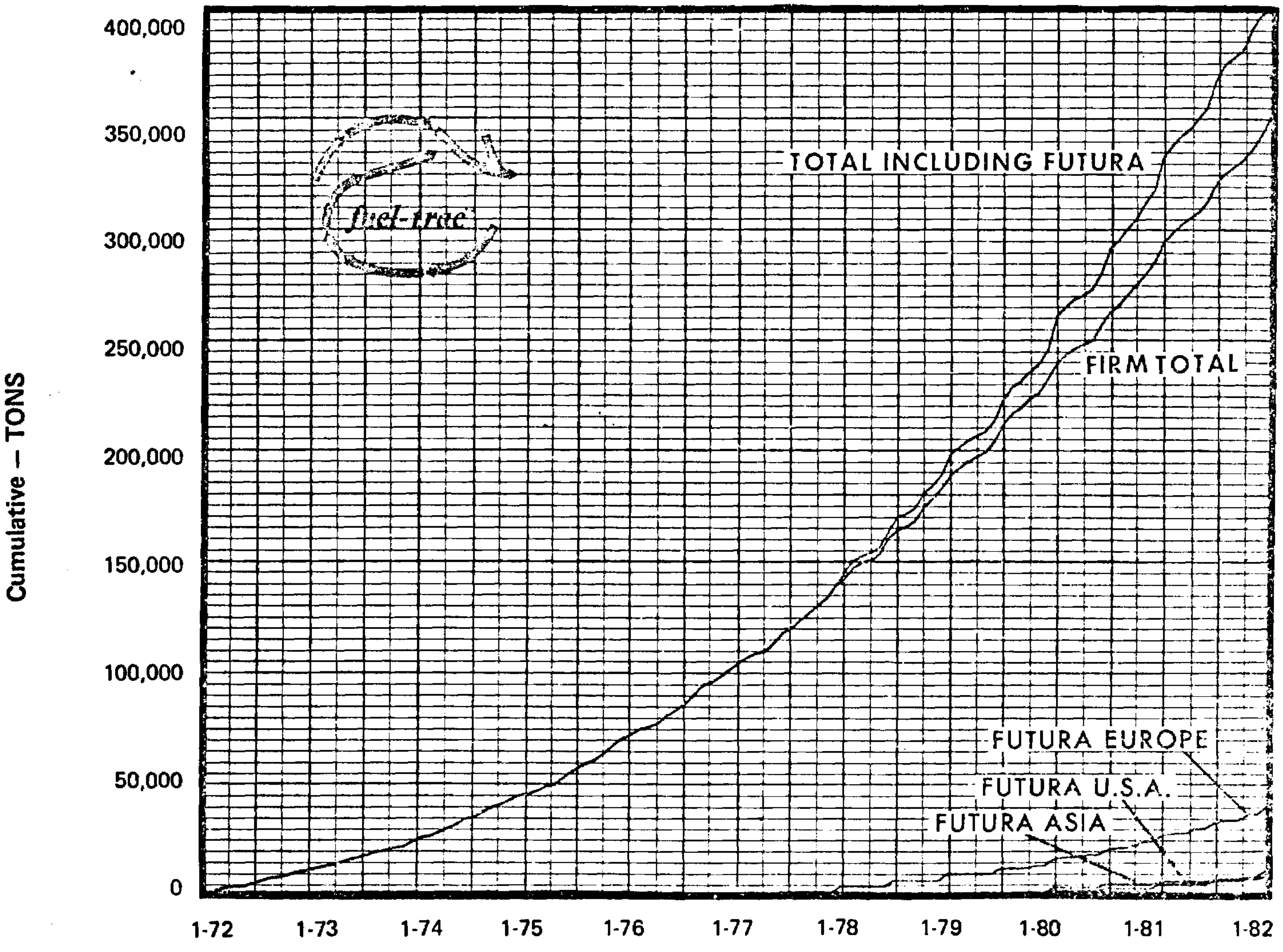


TABLE 1.1

ANNUAL REQUIREMENTS BREAKDOWN—TONS

	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
FIRM TOTAL *	10849	14195	19835	27124	32271	38097	46500	50439	55140	56562
FUTURA										
U.S.A.	0	0	0	0	0	0	0	3494	3204	5721
EUROPE	0	0	0	0	0	3094	6292	6938	10841	13894
ASIA	0	0	0	0	0	0	0	1811	3217	4163
FUTURA TOTAL	0	0	0	0	0	3094	6292	12243	17262	23778
FIRM + FUTURA TOTALS	10849	14195	19835	27124	32271	41191	52793	62683	72402	80340

* Includes Reactors not in U.S.A., Europe and Asia

U. S. A. URANIUM ORE PROCESSING

Firm Cumulative Requirements – First Cores & Reloads

GRAPH 5

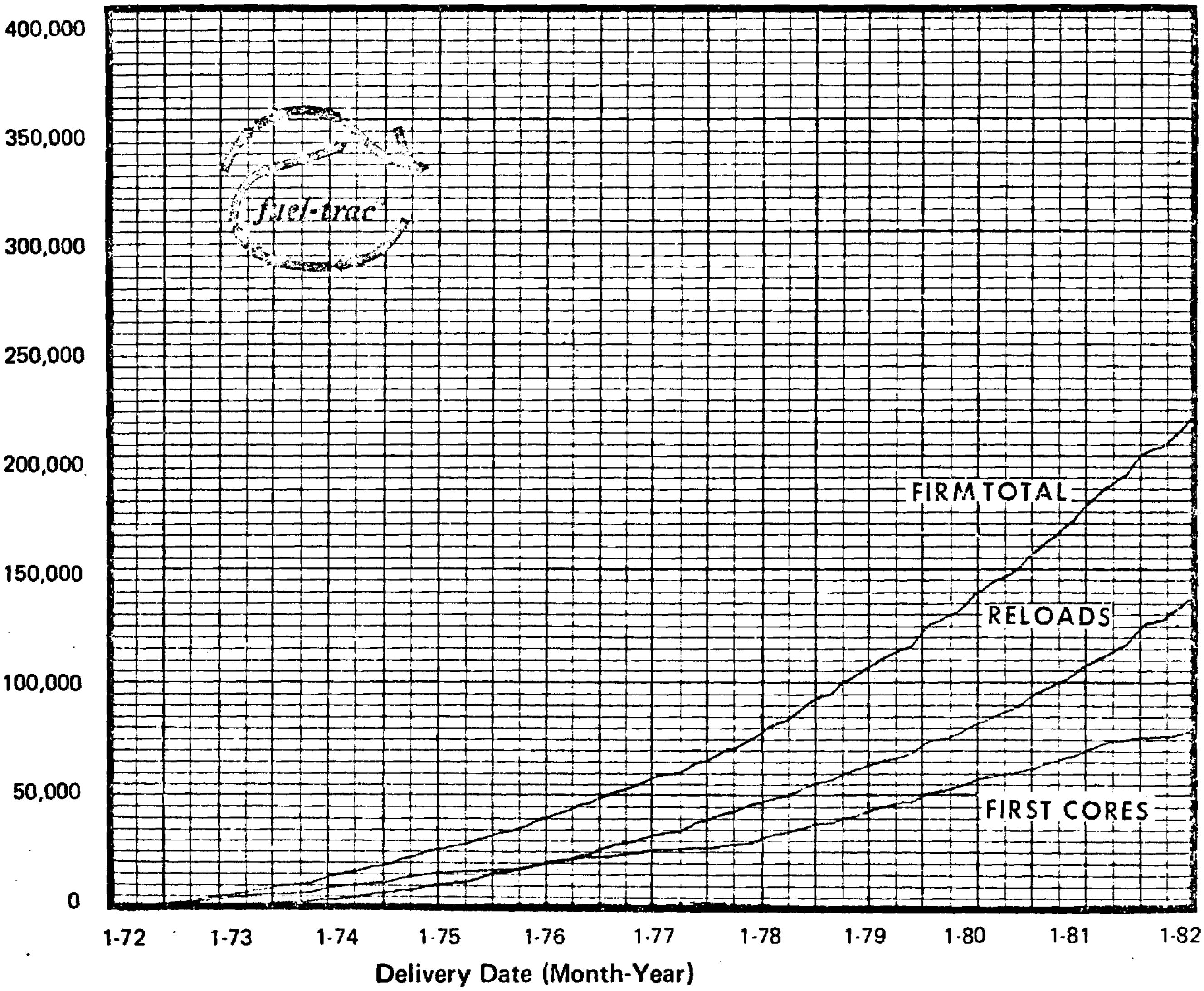


TABLE 1.2

FIRM ANNUAL REQUIREMENTS BREAKDOWN–TONS
First Cores & Reloads

	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
ST CORES	4967	5376	5822	4396	5761	4284	12549	14083	12023	8603
NNUAL TOTAL	77	61	49	31	32	22	43	43	32	22
.OADS	1455	3436	6003	9564	12231	14769	16418	18203	25412	30610
NNUAL TOTAL	23	39	51	69	68	76	56	56	67	78
M TOTAL	6422	8812	11825	13960	17992	19053	28967	32286	37435	39213
IULATIVE TOTAL	6422	15234	27059	41019	59011	78064	107031	139317	176752	215965

U_3O_8 – UF_6 CONVERSION

U. S. A., Europe, Asia

Cumulative Requirements

GRAPH 6

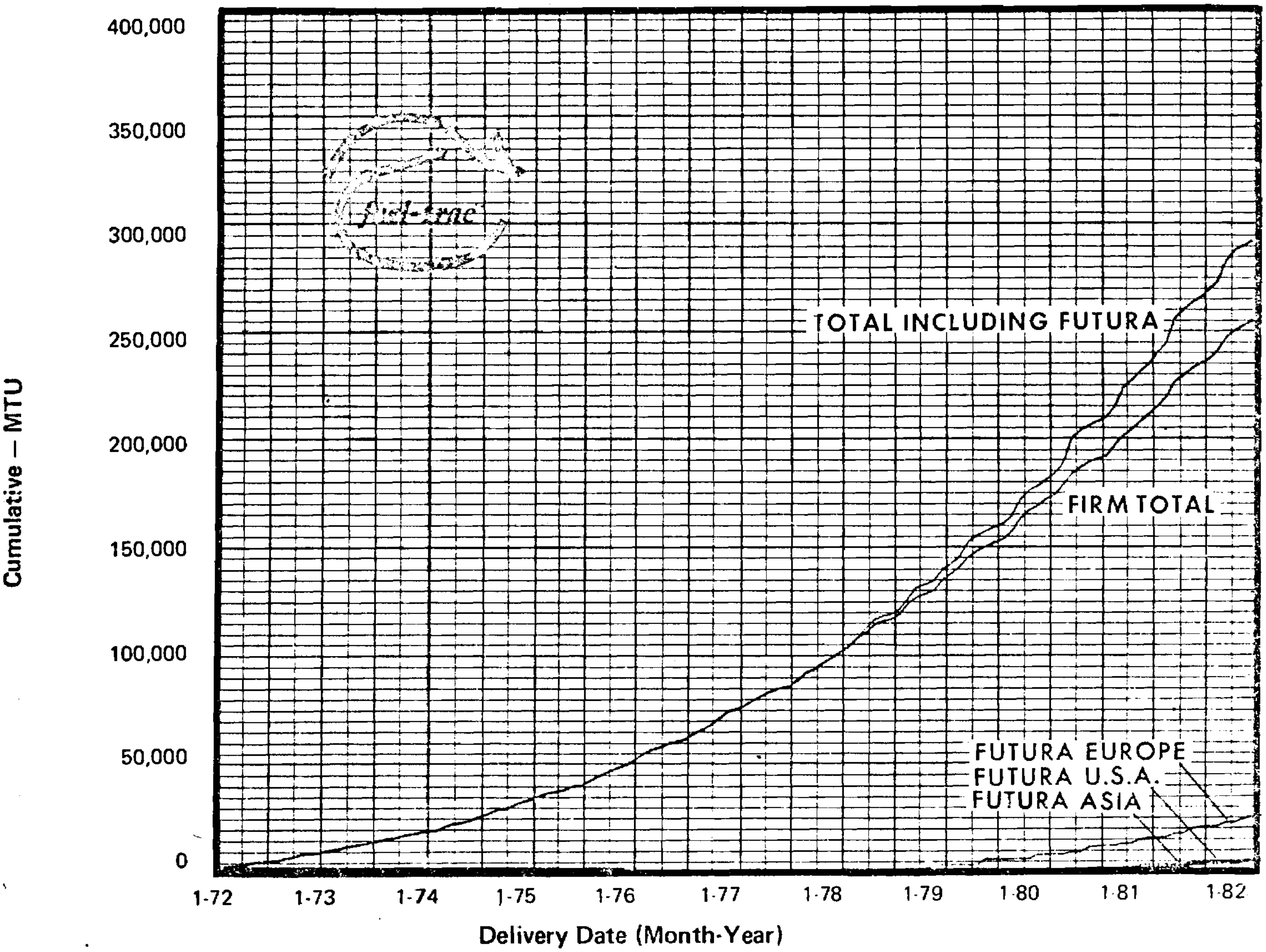


TABLE 2.1

ANNUAL REQUIREMENTS BREAKDOWN – MTU

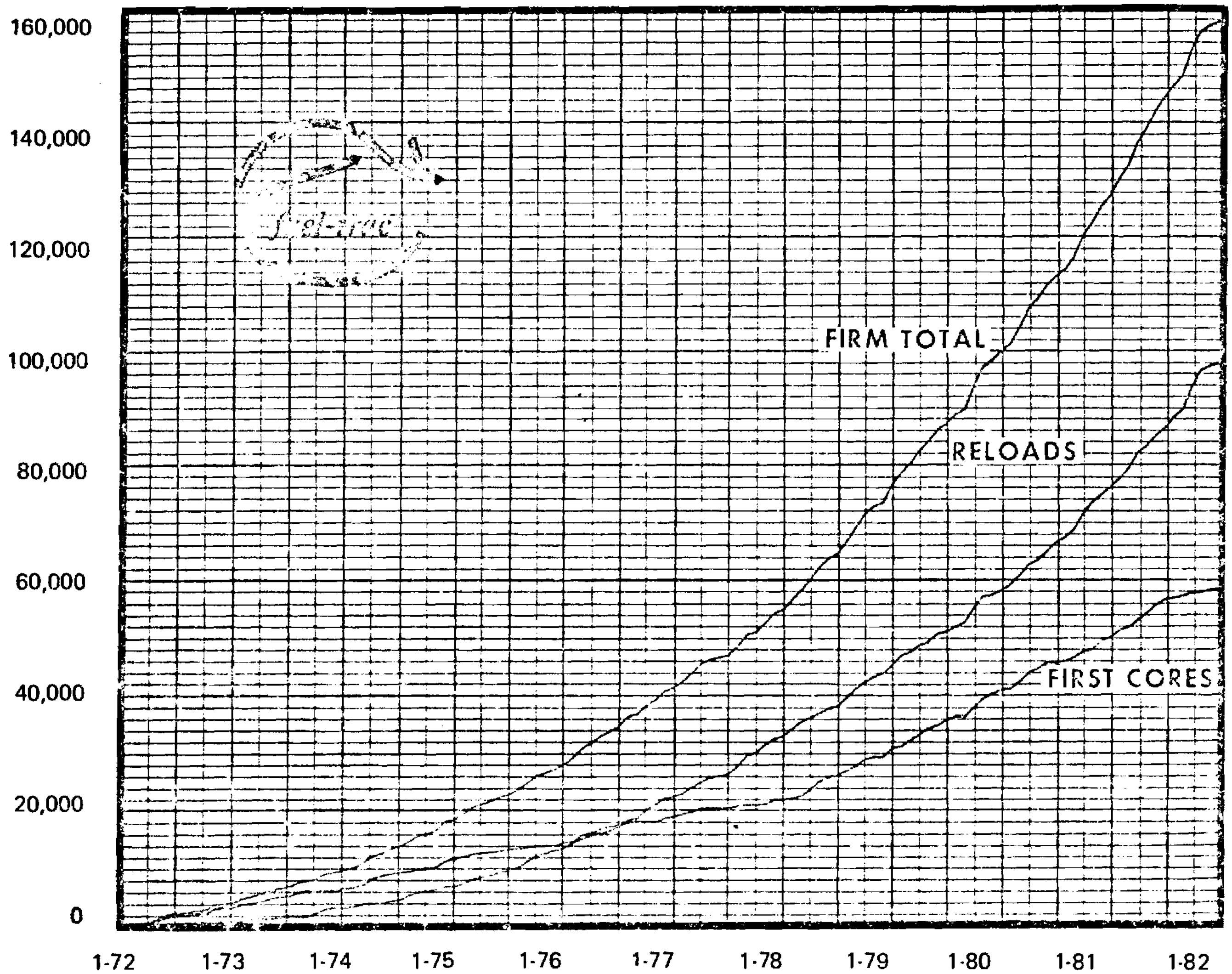
	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
FIRM TOTAL*	7032	10070	15138	18189	24225	26650	34146	37462	39452	43318
FUTURA										
U.S.A.	0	0	0	0	0	0	0	0	4027	2003
EUROPE	0	0	0	0	0	0	4566	4618	7497	9671
ASIA	0	0	0	0	0	0	0	0	2439	2930
FUTURA TOTAL	0	0	0	0	0	0	4566	4618	13963	14604
FIRM + FUTURA TOTALS	7032	10070	15138	18189	24225	26650	38712	42080	53415	57922

* Indicates Reactors Not in U.S.A., Europe and Asia

U. S. A. U_3O_8 – UF_6 CONVERSION

Cumulative Requirements — First Cores & Reloads

GRAPH 7



Delivery Date (Month-Year)

TABLE 2.2

ANNUAL REQUIREMENTS BREAKDOWN – MTU
First Cores & Reloads

	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
RST CORES	3234	3277	5218	2822	4409	3075	9053	10162	9126	8345
ANNUAL TOTAL	79	57	59	29	33	23	41	43	34	28
LOADS	744	2472	3603	6776	9088	10507	12416	13020	18027	21691
ANNUAL TOTAL	18	43	41	71	67	77	57	56	66	72
M TOTAL	3978	5749	8821	9598	13497	13582	21469	23182	27153	30036
MULATIVE TOTAL	3978	9727	18548	28146	41643	55225	76694	99876	127029	157065

U. S. A. Reactors

Firm Cumulative Requirements & Commitments

GRAPH 8

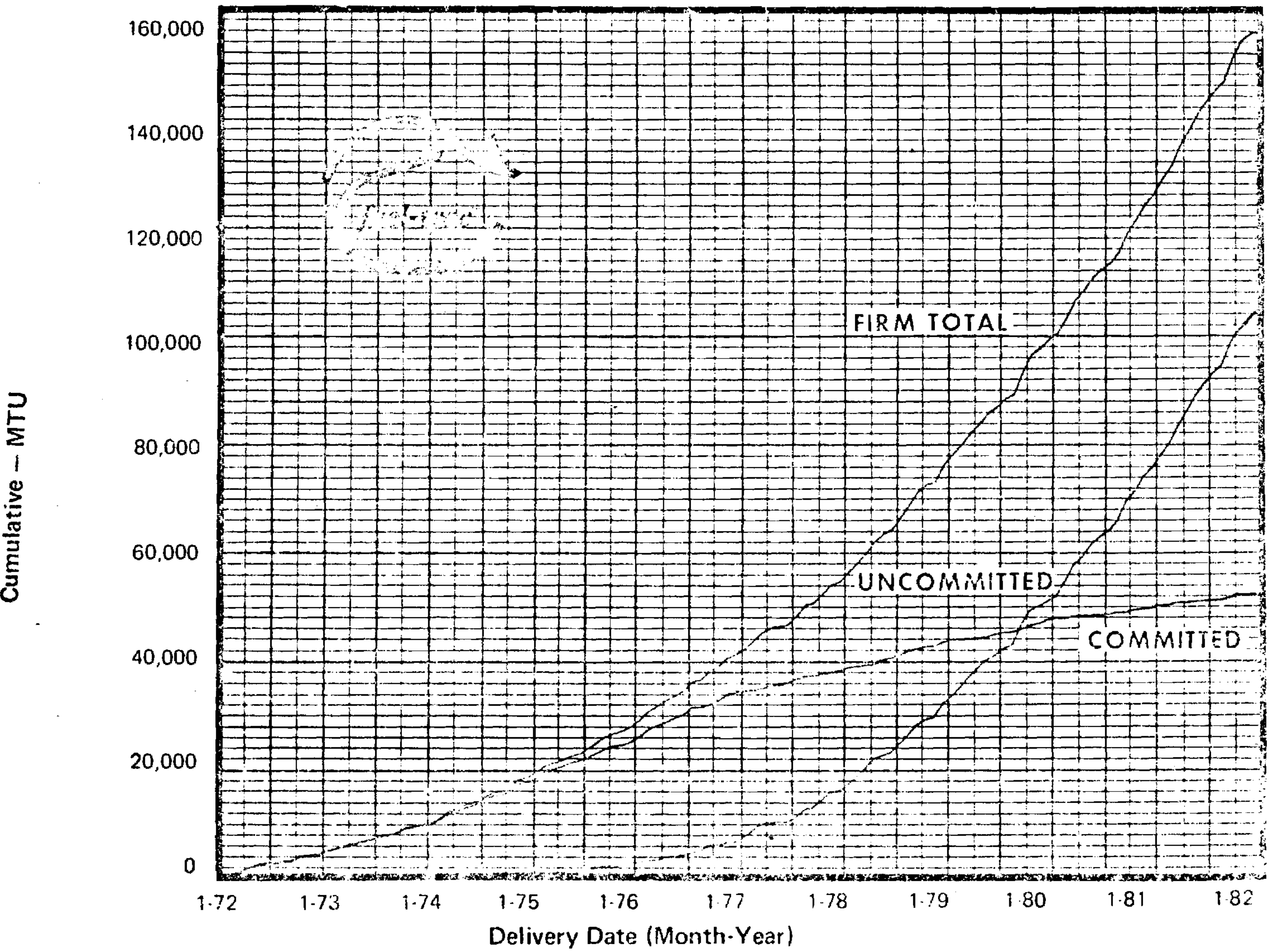


TABLE 2.5

FIRM ANNUAL COMMITMENTS BREAKDOWN – MTU
First Cores & Reloads

	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
COMMITTED TO PROCESSORS	3948	5646	8049	7717	9437	3984	5522	4260	2283	2824
% ANNUAL TOTAL	99	98	91	80	70	29	26	18	8	9
UNCOMMITTED TO PROCESSORS	30	104	772	1881	4060	9598	15947	18922	24871	27407
% ANNUAL TOTAL	1	2	9	20	30	71	74	82	92	91
FIRM TOTAL	3978	5750	8821	9598	13497	13582	21469	23182	27154	30231
CUMULATIVE TOTAL	3978	9728	18549	28147	41644	55226	76695	99877	127031	157262

URANIUM ENRICHMENT

U. S. A., Europe, Asia

Cumulative Requirements

GRAPH 9

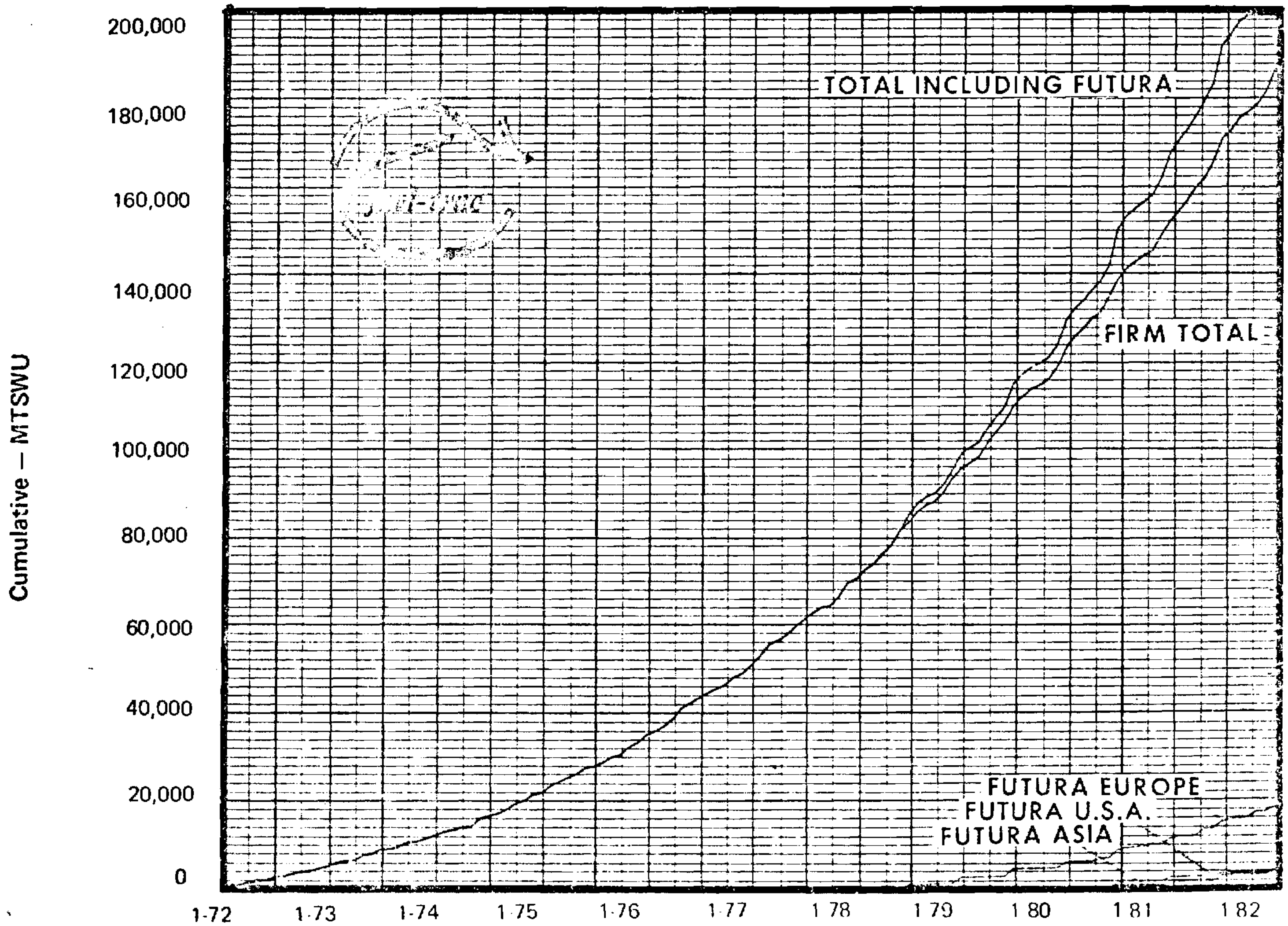


TABLE 5.1

ANNUAL REQUIREMENTS BREAKDOWN–MTSWU

	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
FIRM TOTAL *	4605	6968	9777	13286	16183	19607	25274	27618	29339	34758
FUTURA										
U.S.A.	0	0	0	0	0	0	0	0	2668	1008
EUROPE	0	0	0	0	0	0	3353	2936	5177	6985
ASIA	0	0	0	0	0	0	0	0	1618	2002
FUTURA TOTAL	0	0	0	0	0	0	3353	2936	9462	9995
FIRM + FUTURA TOTAL	4605	6968	9777	13286	16183	19607	28627	30554	38802	44753

* Includes Reactors not in U.S.A., Europe and Asia.

WORLDWIDE SEPARATIVE WORK REQUIREMENTS AND USAEC CAPABILITY

(With CIP and CUP at 0.3% Tails Assay)

GRAPH 10

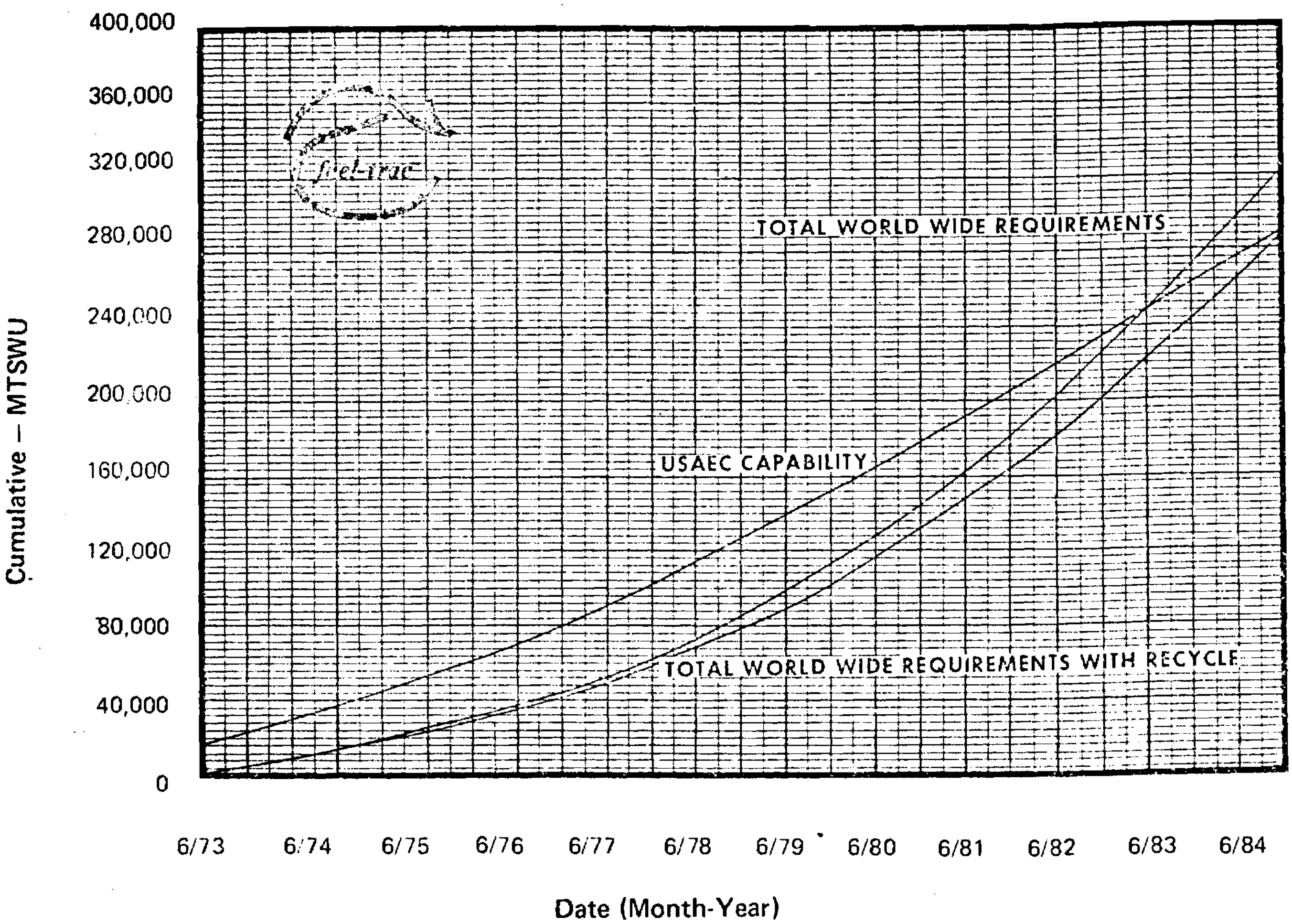


TABLE 5.5

ANNUAL REQUIREMENTS BREAKDOWN--MTSWU

	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
	5500	7729	10514	12799	15527	20007	21875	23269	27581	27425	27346	26857
**	0	0	0	0	0	2738	2297	7542	7915	13037	16988	23572
	5500	7729	10514	12799	15527	22745	24172	30811	35496	40462	44334	50429
OF CLED URANIUM	421	177	192	237	298	412	452	579	756	851	1056	1128
OF CLED PLUTONIUM	246	289	442	783	1282	1783	2152	2634	3364	4325	5418	6212
W/RECYCLE	4833	7263	9880	11779	13947	20550	21568	27598	31376	35286	37860	43089

...ance for uranium recycle and includes allowance for plutonium recycle where definite plans exist.
...ance for uranium recycle and includes allowance for plutonium recycle where vendor expresses definite plans.

U. S. A., Europe, Asia

Firm Reactors

GRAPH - 11

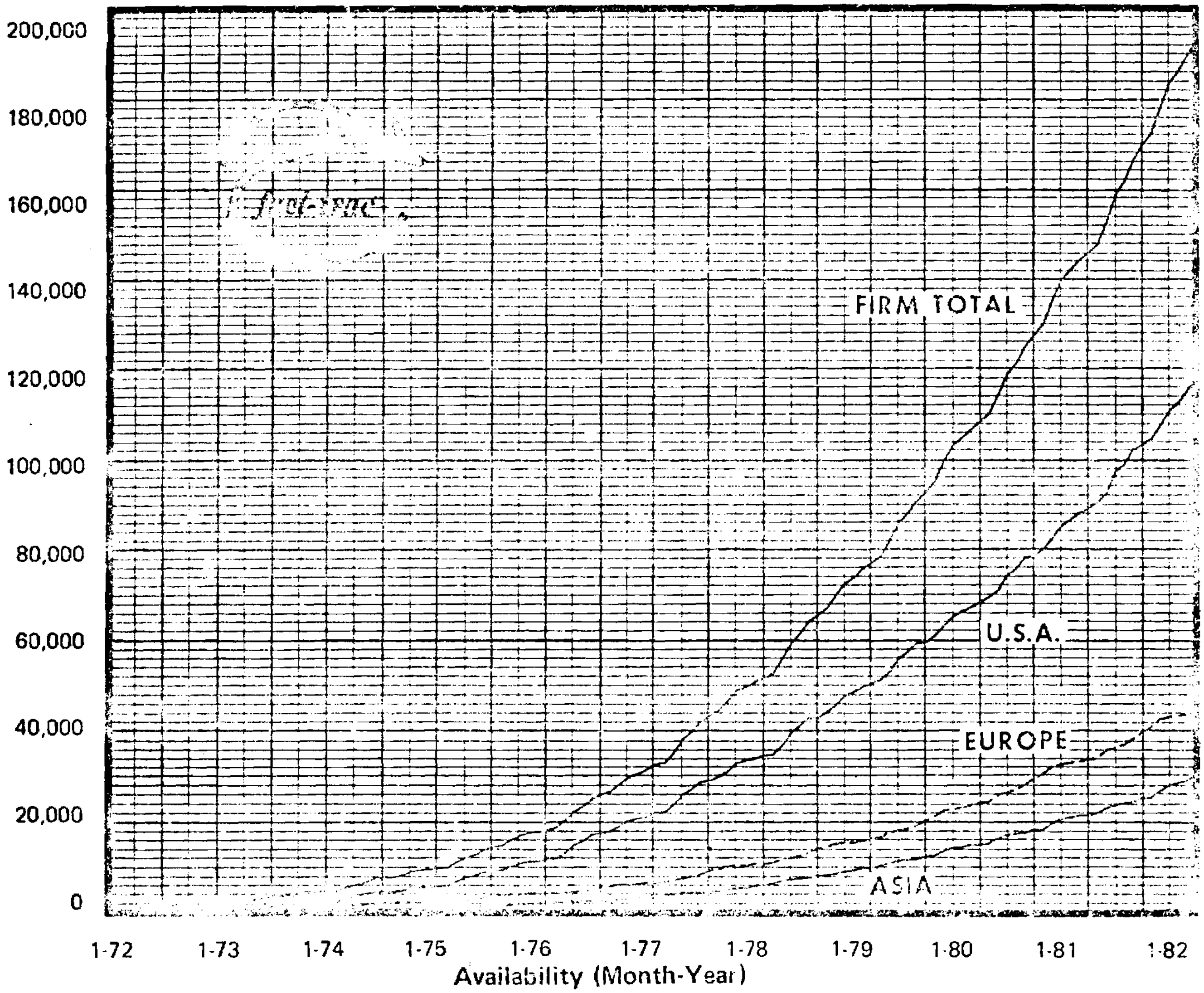


TABLE 9.2

ANNUAL DISCHARGE BREAKDOWN – KgPU

	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
U.S.A.	1268	1178	3184	5764	9935	12993	15853	17728	20944	27079
EUROPE	583	1052	1100	1703	2403	4212	5095	7820	9798	10464
ASIA	183	495	661	749	1572	2339	3999	5195	6567	7792
FIRM TOTAL	1947	2725	4945	8216	13910	19544	24947	30743	37309	45335
CUMULATIVE TOTAL	1947	4672	9617	17833	31743	51287	76234	106977	144286	189621

PLUTONIUM

U. S. A., Europe, Asia

GRAPH 12

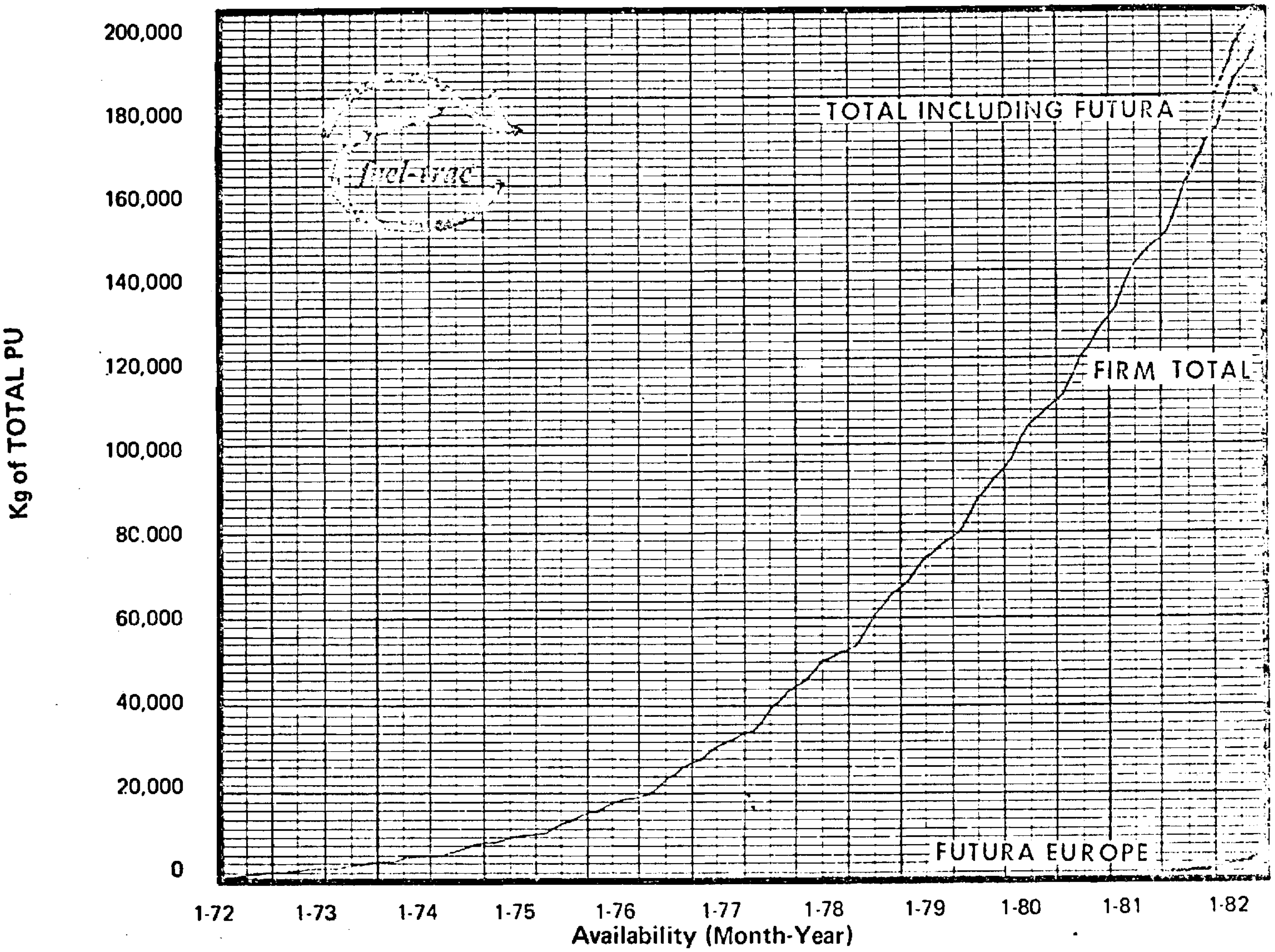


TABLE 9.1

ANNUAL DISCHARGE BREAKDOWN – KgPU

	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
FIRM TOTAL*	2034	2725	4945	8215	13910	19543	25140	31039	37615	45638
FUTURA										
U.S.A.	0	0	0	0	0	0	0	0	0	0
EUROPE	0	0	0	0	0	0	0	0	1318	4732
ASIA	0	0	0	0	0	0	0	0	0	0
FUTURA TOTAL	0	0	0	0	0	0	0	0	1318	4732
FIRM + FUTURA TOTALS	2034	2725	4945	8215	13910	19543	25140	31039	38933	50371

* Includes Reactors not in U.S.A., Europe and Asia.

UO_2 POWDER PRODUCTION

U. S. A., Europe, Asia

Cumulative Requirements

GRAPH 13

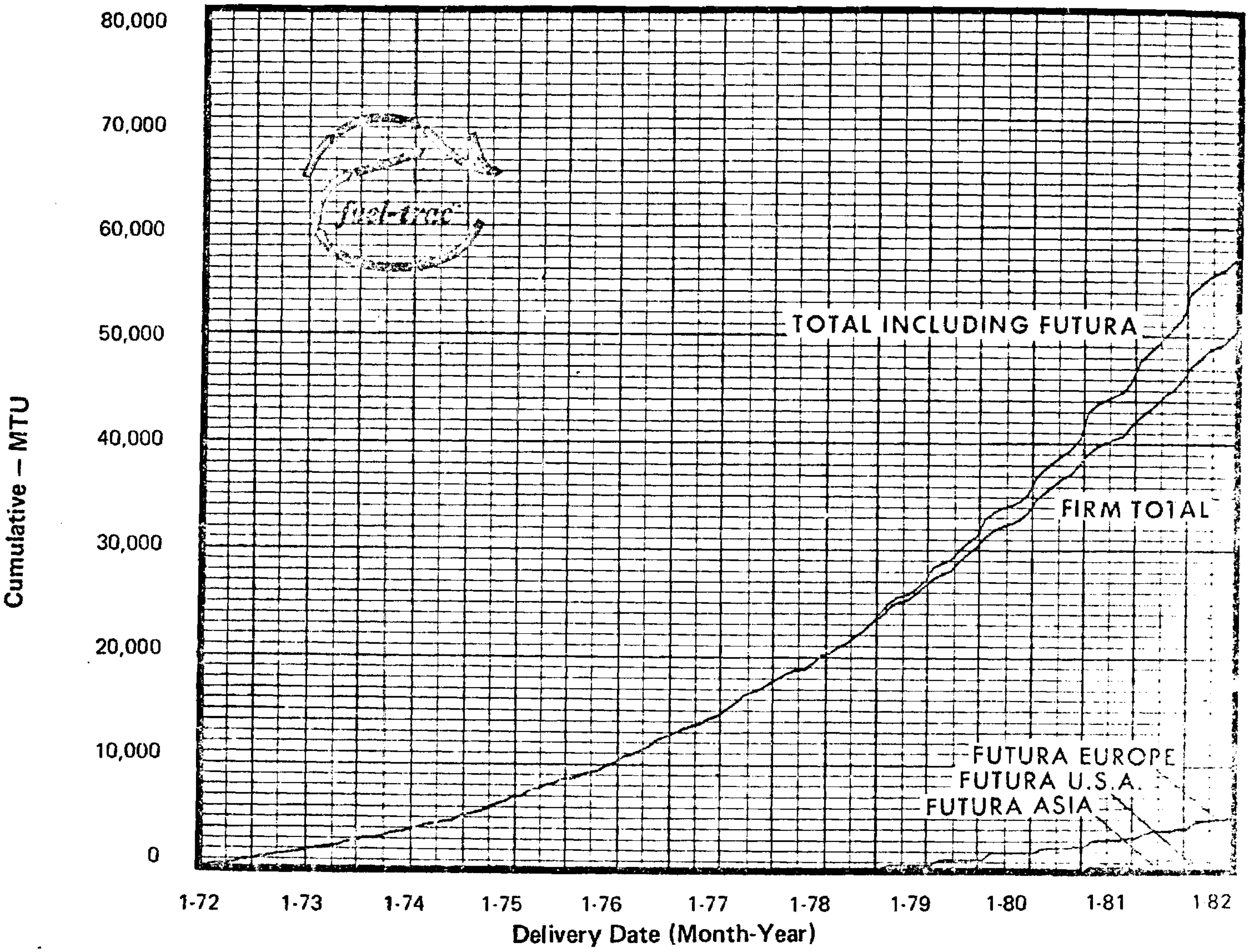


TABLE 6.1
ANNUAL REQUIREMENTS BREAKDOWN – MTU

	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
FIRM TOTAL *	1552	2025	3080	3226	4490	5711	6582	6928	8109	8600
FUTURA										
U.S.A.	0	0	0	0	0	0	0	0	674	655
EUROPE	0	0	0	0	0	0	495	1198	1428	1981
ASIA	0	0	0	0	0	0	0	0	352	589
FUTURA TOTAL	0	0	0	0	0	0	495	1198	2454	[illegible]
FIRM + FUTURA TOTALS	1552	2025	3080	3226	4490	5711	7077	8126	10564	11914

* Includes Reactors not in U.S.A., Europe and Asia

UO_2 POWDER PRODUCTION

U. S. A., Europe, Asia

Firm Cumulative Requirements

GRAPH 14

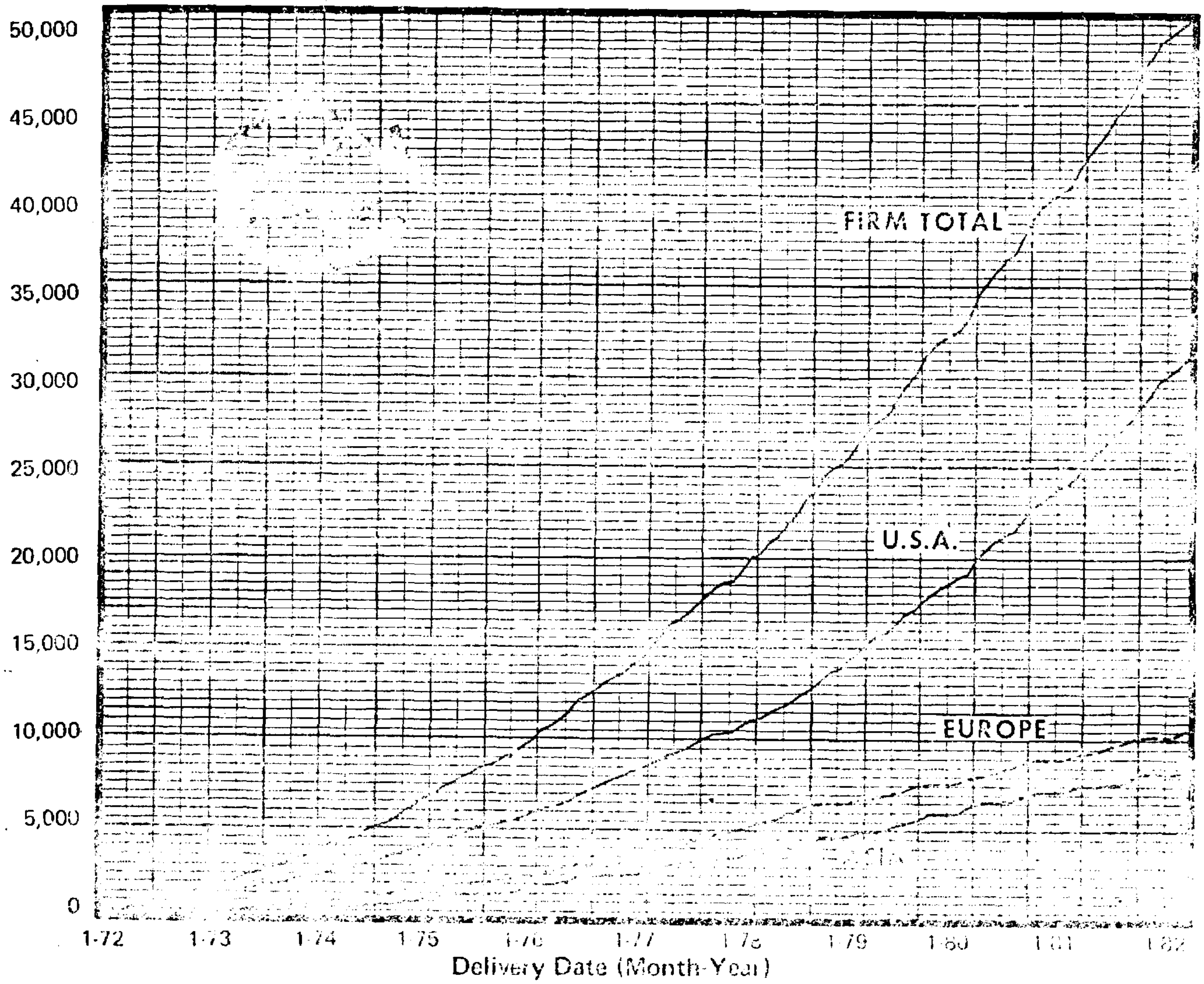


TABLE 6.2

ANNUAL REQUIREMENTS BREAKDOWN – MTU

	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
U.S.A.	1209	999	1809	1849	2409	2803	3782	4354	5478	6485
EUROPE	136	663	831	712	1093	1768	1540	1135	1412	1232
ASIA	197	362	440	665	851	1140	1224	1398	1183	936
FIRM TOTAL	1542	2024	3080	3226	4353	5711	6546	6887	8073	8653
CUMULATIVE TOTAL	1542	3566	6646	9872	14225	19936	26182	33369	41412	50[illegible]

U. S. A., Europe, Asia

GRAPH 15

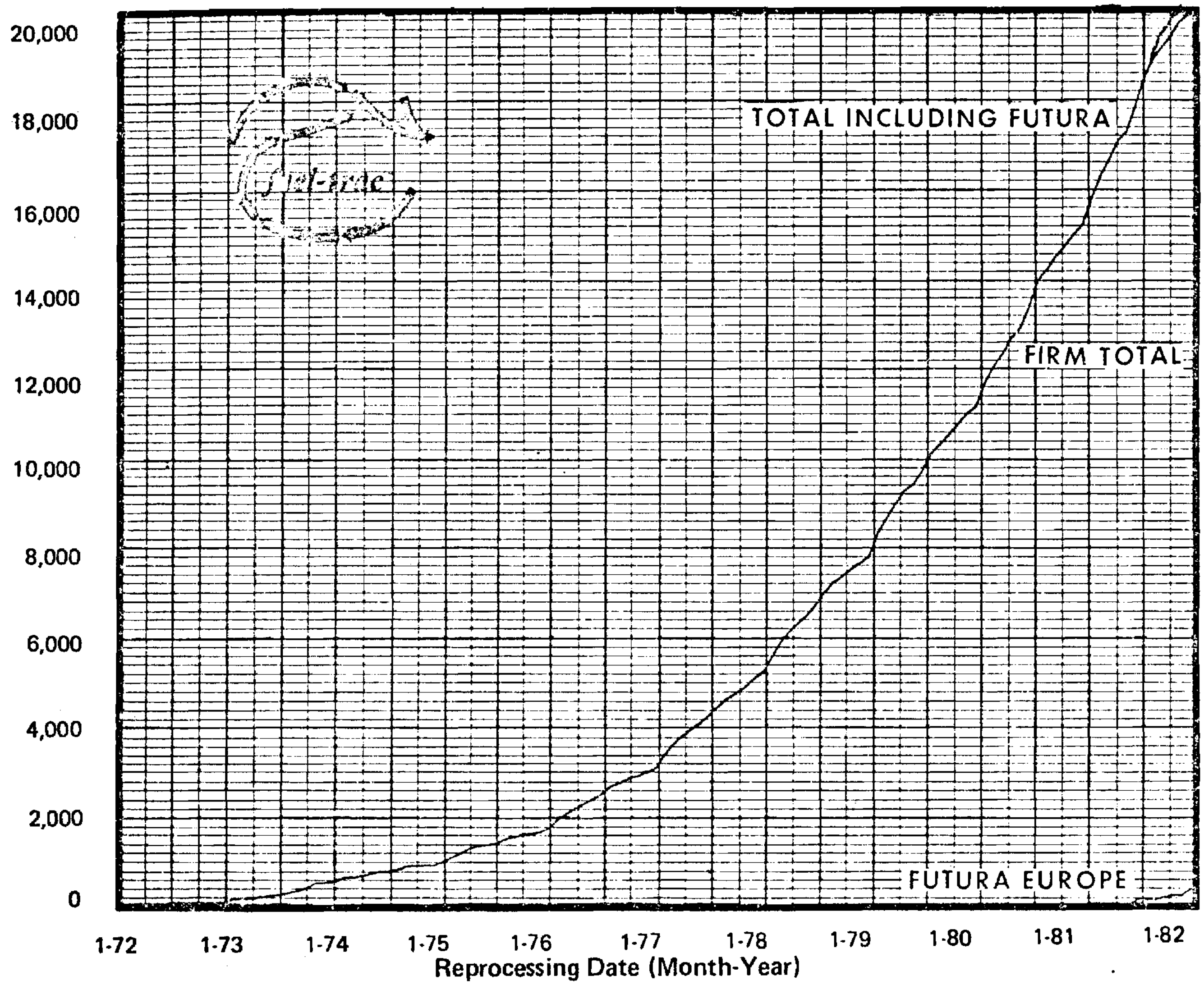


TABLE 8.1

ANNUAL REQUIREMENTS BREAKDOWN – MTU

	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
FIRM TOTAL*	192	488	468	837	1455	2170	2783	3383	4100	4903
FUTURA										
U.S.A.	0	0	0	0	0	0	0	0	0	0
EUROPE	0	0	0	0	0	0	0	0	0	422
ASIA	0	0	0	0	0	0	0	0	0	0
FUTURA TOTAL	0	0	0	0	0	0	0	0	0	422
FIRM + FUTURA TOTALS	192	488	468	837	1455	2170	2783	3383	4100	5325

* Includes Reactors not in U.S.A., Europe and Asia.

PROJECTION BY REACTOR TYPES

There is a vast literature on the engineering and design considerations safety and environmental - for the various reactors which are under construction. Figure 1 illustrates the various reactor types. These are the pressurized water reactor system, the direct cycle boiling water reactor, the gas-cooled reactor system, and the fast breeder reactor system. Of course, both the pressurized water reactor and the boiling water reactor systems utilize light water as moderator and coolant. The advantage of course being that water is a well documented heat transfer medium and a relatively simple cooling system. It is interesting to note that the present development of the light water reactors holds its present status largely due in part to federal sponsorship. To quote from Rose[7]

> "The light water devices were developed either with federal money (as part of the nuclear submarine program of Westinghouse Electric Corporation) or with conscious acceptance of initial losses such as those incurred by the General Electric Company in promoting the boiling water reactor. The high temperature gas-cooled reactor may actually be safer than the water reactors, more economical of uranium resources, more efficient, meaning that less heat is rejected to the environment and perhaps even cheaper to build, although not all of these advantages are confirmed. Its development lagged because the sponsor, the General Atomic Division of General Dynamics could not afford to accept losses on initial units. Now that General Atomic is part of the Gulf Oil corporation, that limitation has been removed; a first reactor is nearing operation and there are six more on order."

Graph 3 taken from Reference 5 (page 18 of this report is a projection of the share of the reactor market which the gas-cooled reactor is expected to power. The same figure also projects reactors to be built by, Westinghouse, General Electric, Babcock and Wilcox, and Combustion Engineering.

THE FAST BREEDER REACTOR

The economically recoverable energy from ordinary nuclear reactors is ~300 x 10^{12} watt-years in the United States according to Starr[8], as shown in Table 2.

TABLE 2[8]

Depletable Supply (10^{12} Watt-Years)	World	U.S.
Coal	670 - 1,000	160 - 230
Petroleum	100 - 200	20 - 35
Gas	70 - 170	20 - 35
Subtotal	840 - 1,370	200 - 300
Nuclear (Ordinary Reactor)	~3,000	~300
Nuclear (Breeder Reactor)	~300,000	~30,000
Cumulative Demand 1960 to Year 2000 (10^{12} Watt-Years)	350 - 700	100 - 140

> "Economically recoverable fuel supply is an estimate of the quantities available at no more than twice present costs. U.S. reserves of all fossil fuels are slightly less than a fourth of the world total. Fossil-fuel reserves are barely equivalent to twice the cumulative demand for energy between 1960 and 2000. Even nuclear fuel is none too plentiful if one were to use only the ordinary light-water reactors. By employing breeder reactors, however, the nuclear supply can be amplified roughly a hundred fold. (10^{12} x 10^{15} BTU)"[8]

The fast breeder reactor permits the recovery of much of the available energy in uranium and thorium. This occurs because during fission in the fast breeder more than two neutrons are released per neutron absorbed. On the average, slightly more than one neutron is necessary for sustaining the fission process, and the extra neutron can be absorbed in non-fissionable uranium-238. As the uranium-238 absorbs the extra neutron it is transformed into fissionable plutonium-239. Thus, while the fast reactor is sustaining the fission process and thereby creating energy, it is also generating fresh fuel which can later be used to create more energy. Reactors which have a breeding ratio greater than 1 create more fuel than they need for their own purposes, and the extra plutonium transformed from uranium-238 can be used to fuel new breeder reactors. By this means, up to 80% of the available energy in uranium can be recovered and used in reactors.

The fast breeder reactor gets its name from its ability to breed, that is to create more fissionable material than it consumes; and from the fact that its neutrons travel faster than they do in a thermal reactor. The breeding process depends, in part, upon the neutrons maintaining a high speed, or high energy. If their speed or energy is allowed to degrade as occurs in thermal reactors, the number of neutrons produced per absorption in uranium or plutonium decreases. Furthermore, at lower velocities, neutrons tend to be captured in various structural materials of the reactor, and this further reduces the breeding potential. It is important, therefore, in fast reactors to keep the velocity of the neutrons high. Water, which is used as a coolant in some thermal reactors, tends to slow the neutrons down and thus prevent efficient breeding. Therefore it is necessary to use a coolant which does not slow the neutrons or capture them as they travel through the coolant.

Considerable research and development has been carried out on the liquid metal cooled fast breeder reactor LMFBR. Another reactor concept, chiefly developed in the United States by Gulf General Atomic is the gas cooled fast breeder reactor GCFRB.

Creagan[9] summarized the LMFBR work to date as of February 1973. Table 3[9] represents national commitments of several countries toward development of the LMFBR.

TABLE 3 National Investments in LMFBR

	Country					
	U. S.	U.S.S.R.	France	U. K.	Japan	Germany
LMFBR/year ($ millions)	200	200	100	70	50	30
1972 GNP ($ billions)	1113	538	162	128	232	195
Percentage of GNP	0.018%	0.04%	0.06%	0.055%	0.02%	0.015%

World status and plans for LMFBR power plants are given in Table 4[9], which lists LMFBR projects that are operable, under construction, planned and decommissioned with country location, megawatts thermal and electric, and initial operation date. Table 4 also shows whether a loop or pool configuration is used.

Present plans for the U.S. LMFBR program in the 1970's consist of completion of the 400 MWt Fast Flux Test Facility (FFTF) on the AEC's Hanford Reservation in the state of Washington. It will not produce electric power but will reject heat to an air heat exchanger. The Hanford Engineering Development Laboratory is operated for the AEC by Westinghouse Hanford Company. The FFTF, when completed in the mid-1970's will be used for testing fuels and materials. It will provide an environment typical of that to be found in future LMFBR's. The reactor will contain closed loops for advanced fuel tests, which will be isolated from process sodium in the main

TABLE 4 Liquid-Metal-Cooled Fast-Reactor Projects

Name	Country	Power MWt	Power MWe	Pool or Loop	Initial Operation
<u>Operable</u>					
BR-5	U.S.S.R	5[a]	-	Loop	1959
DFR	U.K	72	14	Loop	1959
EBR-II	U.S.	62.5	16	Pool	1963
BN-350	U.S.S.R.	1000[b]	150	Loop	1973
PHENIX	France	600	250	Pool	1973
RAPSODIE	France	40	-	Loop	1967
BR-60 (BOR)	U.S.S.R.	60	12	Loop	1970
<u>Under Constr.</u>					
PFR	U.K.	600	250	Pool	1972
FFTF	U.S.	400	-	Loop	1977
JOYO	Japan	100[c]	-	Loop	1974
BN-600	U.S.S.R	1500	600	Pool	1976
KNK-11	W. Germany	58	20	Loop	1973
PEC	Italy	140	-	Modified Pool	1976
SNR	W. Germany[d]	730	300	Loop	1977
DEMO No. 1	U.S.	750-1250	300-500	Loop	?
MONJU	Japan	750	300	Loop	1978
DEMO No. 2	U.S.	750-1250	300-500	Not Decided	?
CFR	U.K.	3125	1320	Not Decided	1979
PHENIX 1000	France[e]	2500	1000	Pool	1979
SNR 2000	Germany	5000	2000	Loop	1983
<u>Decommissioned</u>					
FERMI	U.S.	200	60.9	Loop	1963
SEFOR	U.S.	20	-	Loop	1969
CLEMENTINE	U.S.	0.025	-	Loop	1946
EBR-1	U.S.	1	0.2	Loop	1951
BR-2	U.S.S.R.	0.1	-	Loop	1956
LAMPRE	U.S.	1	-	Loop	1961

a- To be increased to 10 MWt in 1972; b- Dual purpose; 150 MWe for electric power and 200 MWe equivalent for desalination.
c- To be operated at 50 MWt initially; d- In cooperation with Belgium and The Netherlands; e- Tripartite effort France, German and Italian electric utilities

reactor coolant loop so that test failures will not harm the reactor.

In addition to the FFTF, the highest priority U.S. LMFBR program is construction of a demonstration plant.

In the latter part of 1973 contracts were signed for the breeder demonstration plant. According to Nuclear News[10] the Project Management Corporation will provide over-all management and coordination design contractor and operation of the facility.

> "The AEC and PMC each signed a contract with the Breeder Reactor Corporation which represents the public utilities contributing to the project.
>
> Under the terms of the main contract, the AEC will seek statutory authority to have two representatives on the PMC board, which now has two members from the TVA, two from Commonwealth Edison, and one designated by the BRC. The parties to the contract had previously established a project steering committee composed of three members -- one each designated by the AEC, the TVA, and Edison. The steering committee will implement management of the project and will administer the contract. The steering committee would become an executive committee of the PMC board, when the AEC is represented on the board, subsequent to the passing of the legislation.
>
> By contract, the general project management authority and responsibility are vested in the PMC board and the steering committee."

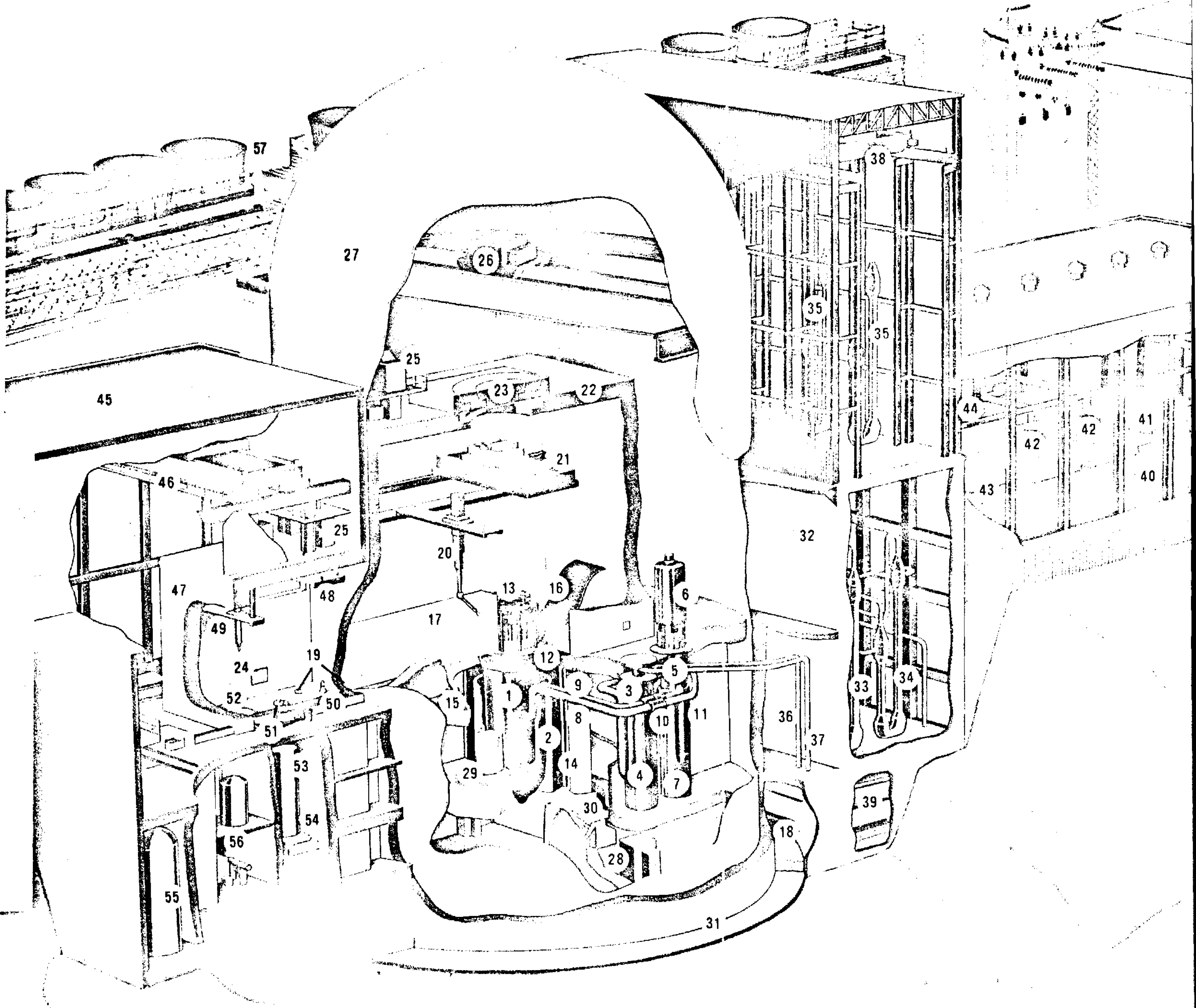
Over $240 million has already been pledged by the electric utility industry for the first demonstration plant, which will be built on the Tennessee Valley Authority system. The total cost of this plant is estimated at about $500 million.

Two organizations have been established to implement this project. The Breeder Reactor Corporation's (BRC) 17 man board represents both investor-owned and consumer-owned utilities, plus the Edison Electric Institute, the American Public Power Association, and the National Rural Electric Cooperative Association. The BRC will provide senior counsel, manage financial contributions to the project, serve as a liaison with the Nation's utilities, and handle the dissemination of information.

The board of the Project Management Corporation (PMC) includes one representative from the BRC, two from TVA, and two from Commonwealth Edison Company, Chicago. The PMC will be responsible for overall design, engineering, and construction of the plant. Commonwealth Edison has provided the Project Manager and Engineering Manager, and TVA will start up, operate, and maintain the demonstration plant. Represented on the PMC Steering Committee are TVA, Commonwealth Edison, and the AEC. The Westinghouse Electric Corporation has been awarded the contract for the reactor system. Figure 5 is a schematic design of the LMFBR demonstration plant.

FIGURE 5

1. REACTOR VESSEL
2. REACTOR VESSEL GUARD VESSEL
3. INTERMEDIATE HEAT EXCHANGER (IHX)
4. IHX GUARD VESSEL
5. PRIMARY SODIUM PUMP
6. PRIMARY SODIUM PUMP DRIVE MOTOR
7. PRIMARY SODIUM PUMP GUARD VESSEL
8. PRIMARY SODIUM HOT LEG PIPING
9. PRIMARY SODIUM COLD LEG PIPING
10. ISOLATION VALVE
11. CHECK VALVE
12. REACTOR CLOSURE HEAD
13. CONTROL ROD DRIVE MECHANISMS
14. SHIELDING
15. OPERATING FLOOR
16. POWER AND INSTRUMENT CABLES
17. EX-VESSEL TRANSFER MACHINE HOUSING
18. PRIMARY SODIUM STORAGE TANKS
19. FUEL STORAGE TANK PORT
20. OVERHEAD MANIPULATOR
21. REFUELING HOT CELL CRANE
22. REFUELING HOT CELL (UNDER-THE-PLUG CONCEPT)
23. REFUELING HOT CELL ROOF PORT
24. VIEWING WINDOW
25. HOT CELL ENVIRONMENTAL CONTROL EQUIPMENT
26. CONTAINMENT BUILDING POLAR CRANE
27. CONTAINMENT BARRIER
28. COMPARTMENT COOLING AND INERTING EQUIPMENT
29. PRIMARY SODIUM PURIFICATION EQUIPMENT
30. STAIRWELL
31. REACTOR BUILDING FOUNDATION
32. STEAM GENERATOR BUILDING
33. STEAM GENERATOR-EVAPORATOR
34. STEAM GENERATOR-SUPERHEATER
35. STEAM GENERATOR-SPARE
36. INTERMEDIATE SODIUM COLD LEG PIPING
37. INTERMEDIATE SODIUM HOT LEG PIPING
38. STEAM GENERATOR BUILDING CRANE
39. SODIUM STORAGE TANK
40. TURBINE-GENERATOR BUILDING
41. ELECTRIC GENERATOR
42. L.P. TURBINE
43. H.P. TURBINE
44. MOISTURE SEPARATOR AND REHEATER
45. FUEL SERVICE BUILDING
46. FUEL SERVICE BUILDING CRANE
47. FUEL SERVICE HOT CELL
48. FUEL SERVICE HOT CELL CRANE
49. FUEL SERVICE MANIPULATOR
50. FUEL SERVICE ROTOR DRIVE
51. NEW FUEL TRANSFER VALVE
52. SHIPPING CASK PORT
53. IRRADIATED FUEL SHIPPING CASK AND CART
54. FUEL CANEL
55. EMERGENCY GASEOUS RADWASTE STORAGE TANK
56. GASEOUS RADWASTE SYSTEM EQUIPMENT
57. FORCED DRAFT COOLING TOWERS
58. MAIN STEPUP TRANSFORMER SUBSTATION
59. SWITCHYARD



FBR DESIGN CONSIDERATIONS

There is extensive leterature on fast reactor engineering considerations and fast reactor physics.[10-22] Rather than repeat the detailed papers we will summarize here only the general characteristics which have a beneficial or adverse effect.

Sodium is a metal melting at about 210°F. It has a low cross-section for absorbing and thermalizing neutrons, but its ability to transfer heat is excellent. It has a high boiling point (1640°F) and a low vapor pressure at most temperatures. These properties make it almost ideal for use as a coolant in a reactor. It can be heated to high temperatures without generating pressure and its excellent ability to transfer heat makes it less sensitive to short term disturbances in the surfaces from which the heat is being transferred. Because the coolant system is operating at a low pressure, in the event of a pipe failure, the liquid will not escape as rapidly as occurs with high pressure systems.

Chemical reactivity of sodium is a safety aspect in some respects. During irradiation of fuel many radioactive isotopes are formed known as fission products. Some of the fission products are radioactive in unstable species of elements which decay gradually to stable forms. In some of the fast reactors these fission products are vented or discahrged from the fuel to the reactor into the sodium coolant. In other fast reactors failure in the fuel outer cladding can release these fission products to the sodium. Because of its unique chemical properties, sodium tends to retain some of these fission products, so they are not so readily released to the inert gases such as helium and argon which are used to blanket the sodium. Radioactive iodine, for example, combines with the sodium to form sodium iodide and cesium is retained in the solution. Niobium and certain other solid fission products also tend to be retained in the sodium. However, the sodium does not retain all fission products. Nearly all of the radioactive zenon and krypton gases bubble up to the sodium and are released into the inert cover gas. Thus, the property of sodium to retain some materials acts as a safety advantage since accident or spillage of sodium does not free quantities of fission products. If the sodium were to violate or break through its containers and to burn in the air, the burning is at a constant rate of the order of 2-14 lbs/hr-square foot of exposed surface, and the fission products would not be released rapidly. This would give time to cope with other problems such as containing the fire. Reactiveness of the sodium causes certain undesirable aspects. For example, when exposed to air sodium oxidizes rapidly if it is in the solid state, and, if in the liquid state, it will burn. This burning is at a constant rate and can be extinguished by eliminating oxygen. When exposed to water, sodium will react violently to form hydrogen. The hydrogen in turn can combine with oxygen and increase the reaction energy. Other features, of sodium also make it undesirable for reactor coolant. Irradiation sodium forms the radioisotopes Na-22 and Na-24 which emit gamma radiation. However most of this radiation will decay within a few days. The characteristic of sodium to become radioactive and to contain radioactive products from other sources makes it potentially hazardous.

In practice, the accessability of sodium to human access is limited. One way for accomplishing this in a fast-breeder reactor is to include two separate cooling circuits containing sodium and one containing water. The first circuit circulates the sodium to the reactor core and becomes highly radioactive.

This radioactive circuit is shielded from human acess, and any maintanence can be accomplished by remote mechanisms. The second circuit picks up the heat from the first and in turn transfers the heat to the water circuit without becoming radioactive. Because of the excellent heat transfer characteristics of sodium, these circuits can be used and still have an economically attractive system. Nevertheless, the extra sodium loop is a safety feature which is included at the expense of extra cost.

The undisrable aspects of sodium can be treated in two ways:

(1) All equipment containing radioactive sodium is placed in gas-type cells which exclude oxygen.

(2) Water is used only to transfer the heat from the nonradioactive sodium circuits, and these circuits are designed to withstand the effects of a sodium water reaction.

There are two important neutronic characteristics of fast reactors which are significantly different from those of thermal reactors. These are:

(1) The shortness on lifetime.

(2) The possibility of secondary criticality.

Neutron lifetime is a measure of the time interval between the birth of the neutron when fission occurs, and its capture in uranium or other materials. Thermal reactor neutrons are slowed down by bouncing off hydrogen atoms, if water is a coolant. Neutrons "live" longer than in a fast reactor in which there is no hydrogen or moderator material to slow them before they are captured. This short neutron lifetime was originally thought to be an undesirable feature. Subsequent research has shown that a short lifetime need not be a significant disadvantage provided the instantaneous power coefficient is negative. With a negative instataneous power coefficient, the lengths of neutron lifetime has little effect on amplitude or duration of the energy ramps from the reactor.

Secondary criticality is a somewhat more complex situation. In any reactor system it is necessary for a certain minimum amount of fissionable material to be present before a self-sustaining chain reaction can take place. The self-sustaining chain reaction takes place when the number of neutrons lost from the system or captured is exactly balanced by the number of neutrons which are being generated in the process of the fission. A thermal reactor is so designed that this balance occurs only after the neutrons have been slowed to a thermal energies. In a fast reactor since the neutrons are not slowed down, criticality is achieved without a moderating material.

The characteristic of fast reactors to be able to be critical without the coolant present can result in "secondary criticality". If for example, some of the fuel which would melt and fall to the bottom of the reactor while at the same time rearranging itself into a more dense assembly or arrangement by filling up the passages normally occupied by the coolant then a critical mass could be possible and this new configuration could become an uncontrolled reactor. This potential problem has resulted in considerable study with the consequence that fast reactors are deisgned with great care to avoid possibilities which can lead to a rearrangement of the core and to a more reactive configuration. This can be accomplished by designing the coolant so that the possibility of the loss of a large amount of the coolant capacity is very low, and also by selecting a geometric arrangement which makes the assembly into a more reactive configuration difficult. Additionally, instrumentation to detect the onset of abnormal circumstances which might lead to meltdown can be included. In the past, two fast reactors have acutally experienced partial core meltdown and of both of these reactors the coolant systems and core geometry where such that the secondary criticality did not occur. Although the probability of secondary criticality is very low, most fast reactor systems designed today have included provisions for accommodating energy released during uncontrolled transient from secondary criticality.

One way to avoid secondary criticality is to insure that the coolant integrity is always maintained. To achieve such assurance reactor systems engineers often take great care in the design of the primary coolant circuit. For example, in one type of fast reactor design the core and all the pumps, valves, pipes and heat exchangers which must circulate the primary sodium from the core are positioned within a large tank vessel which is filled with sodium.

It was previously mentioned that an instantaneous negative power coefficient was desirable. A power coefficient is simply a term which describes the response of the reactor to certain stimuli. For instance, if the power is increased by withdrawing control rods which control the nuclear chain reaction, this would normally cause the fuel to increase in temperature and to expand physically. As the core expands from the higher temperature its' height grows slightly and its outside surface area becomes larger. This wll permit a greater number of neutrons to leak out of the core and to be lost from the reactor system, thus tending to reduce the amount of neutrons which are fissioning. This in turn will cause the reactor power increase to be reduced, compared to what would have been the case if the thermal expansion had not occurred. The entire effect is described as thermal expansion power coefficient. It is negative. If the coefficient were positive instead of negative the opposite effect would occur, namely that as power increases in the reactor by withdrawing control rods, this increase would be amplified beyond the movement implied by the control rods.

During the early developments of the fast reactor it became obvious that two particular reactor characteristics were desirable. One of the characteristics was a long fuel lifetime, and the other is a negative power coefficient. A long fuel lifetime which permits leaving the fuel in the reactor for an extended time can yield a low fuel cost. Most of the early reactor designs included uranium fuel in the form of metal. However, under irradiation this metal gradually damaged and had to be removed from the core. By changing the form of the uranium or plutonium metal to uranium or plutonium oxide it is found that the lifetime of the fuel can be extended substantially. Fortunately it is found that using ceramic fuel not only improved the fuel lifetime characteristics but also introduced a prompt negative power coefficient which was as predictable as expansion coefficient in metal fuel. This particular coefficient is known as a Doppler coefficient. Since the ceramic fuel is high temperature material, in order for the fuel to undergo damage it must reach very high temperatures. It is the change in temperature from the operating point to some higher temperature which produces the Doppler effect. This effect which is caused by the heating up of the atoms of the uranium fuel, causing them to move faster. Neutrons which are passing through the fuel tend to be captured by some of the U-238 atoms at what is known as a resonance energy. The increased velocity of uranium atoms increases the number of these atoms which are at the resonance capture and would be relative to the passing neutrons. Thus these U-238 atoms therefore stop some of the neutrons which otherwise would have continued their travel until capture in the fission process, and this effect tends to lower reactivity and power. Again a reactivity or negative power coefficient results. Discovery of the Doppler effect in a fast reactor was an extremely important development.

One of the power coefficients in a sodium cooled fast breeder reactor which is not negative is a sodium void coefficient. If the sodium were to boil down it could be expelled from the coolant channels. Depending upon the geometry of a fast reactor core in the manner in which the sodium is removed, this can result in a positive reactivity effect. This happens because sodium tends to slow neutrons down and reduce the number of fast neutrons available for fissioning. Therefore, when sodium is removed from the core by boiling, not as many atoms are slowed and more fast neutrons are present for the fission process. A competing effect is that the removal of sodium also tends to allow more neutrons to leak from the core and this results in a decrease in the total number of neutrons. The net result of these two competing effects is dependent upon the geometric pattern of the sodium being removed from the core. Under proper conditions the net effect can be to increase the number of neutrons available for fission with a consequent reactivity increase and increase in power level of the core. As previously mentioned, the sodium operates very much like a below the boiling point of the reactor and this reduces the likelihood of boiling. Furthermore, instruments are present to detect conditions which might cause boiling, the reactor can be shut down if anomalies develop.

From the previous discussion of the characteristics of fast breeder reactors, it is clear that some of the characteristics have a beneficial effect on the safety of the reactor and others have an adverse effect. Considerable amounts of experience and design work permit the selection of parameters and design features so as to amplify the desirable characteristics and to deemphasize or properly cope with the undesirable characteristics.

Safety and environmental effects of fast reactors have been questioned even more than thermal reactors. This subject will be discussed further in the next section.

ENVIRONMENTAL ASPECTS OF NUCLEAR POWER STATIONS

To the nuclear industry the term environment means those parts of nature which interact with nuclear operations, namely the atmosphere, the land, surface water, ground water, coastal waters, and the sea. In normal operation nuclear power plants have an interaction on the environment as well as a potentially adverse effect on the environment in the event of an accident. In normal operation, nuclear power plants release a small amount of radioactivity in the effluents - air and water. Additionally, there is a problem of the effect of quantities of waste heat on the water bodies or the atmosphere to which the heat is discharged. The impact of nuclear power stations on the environment have been a continuing study ever since electrical power generation using nuclear reactors became feasible. These problems have been debated, for example at the first United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955. Extensive research has continued.[26] Over the years the International Commission on Radiological Protection has prepared a number of recommendations on dose limits for external and internal exposures and the concentration limits of various radionuclides in air and water. These have been used as a base for determining safe working levels for various forms of radioactive material both occupationally exposed workers and the general public.

The general public has become slowly aware of the side effects resulting from the many spectacular advances in various fields - medicine, agriculture, motor and air transport, and power generation. By the late 1960's the problem of "pollution" had become a topic that aroused strong feelings in the general public in most industrial countries. Many people have expressed concern with atomic energy, nuclear power stations, existing and proposed. The safety of the reactor and relative importance of the effect on the environment has become an extremely controversial issue. In some cases, as a result of intervention, radioactivity limits have been decreased and nuclear power plant startup schedules have been delayed as a result of long public hearings and arguments.

According to reference 24

> "Prior to the issuance of a construction permit or an operating license for a nuclear power plant, the USAEC is required to assess the potential environmental effects of that plant in order to assure that the issuance of that permit or license will be consistant with the national environmental goals as set forth by the Public Environmental Act of 1969 (Public Law 91-190). In order to obtain information essential to this assesment the commission requires each applicant for a permit or license to submit a report on the potential environmental effects of the proposed plant and associated facilities.
>
> The national environmental goals as expressed by the environmental policy act (NEPA) are as follows: 'It is the continuing responsibility of the federal government to use all practical means, consistant with other essential considerations of national policy, to improve and coordinate federal plans functions, program and resources."

Additionally, a cost benefit analysis is required in which alternate site-plant combinations and plant systems are to be examined in order to determine whether the proposed facility is a cost effective choice considering economic, social and other environmental factors and any institutional constraints.

One of the most often discussed topics concerning the social aspects of nuclear power is the biological effect of radiation. It is widely known that sufficient exposure to radiation can be harmful to man. Both the nuclear industry and the population as a whole will be exposed to increased levels of radiation as nuclear power plants increase in number. The genetic effects of radiation have been studied for some time now and a relatively large amount of data is available. However, extrapolation of the data to the low exposures levels from an operating nuclear power plant has been the subject of much controversy[25]. Consequently the effects have been generally estimated by linear extrapolation from data at higher exposure levels. These results must be then compared to exposures from natural and other man-made sources to determine the social impact of increased radiation levels. Exposures from natural sources are shown in Table 5, and exposures from man-made sources are shown in Table 6.

Estimates of the exposure to radiation due to operation of nuclear reactors are given in the Argonne study as the impact on the whole U.S. and world populations. Tables 7 and 8 show the total radiation dose to these populations for nuclear power industries in 1980 and 1990. These data already include factors to account for population size and mean lifetime of radioactive nuclide; and to compare with previous tables 130 man-rad exposure to Kr-85 in the U.S. for the 1980 industry corresponds to a dose rate of about 3×10^{-4} mrad/yr. Thus one can see that the influence of nuclear plant operation to the general population exposure is very slight.

Global effects are not the only exposure effects that must be included however, since the fraction of the population that works in the nuclear industry will receive a proportionally higher exposure. The majority of the exposure comes from reactor operation, mining, and fuel reprocessing. The exposure breakdown for several reactor types is given in Table 9.

It is necessary now to translate the exposure levels that have been estimated to arise from nuclear plants into health effects. There is a large amount of data on somatic effects on laboratory animals, but we would like the somatic and genetic effects on humans. The induction of malignant neoplasms has had the largest attention of radiobiolotists, and estimates

TABLE 5 Average Dose Rates Due to Natural Background

Source of Irradiation	Dose Rate (mrad/yr) Gonad (=total body)	Bone Marrow
External irradiation		
Extraterrestrial sources		
Ionizing component	28	28
Neutrons	0.7	0.7
Terrestrial sources	50	50
Internal irradiation		
K-40	20	15
C-14	0.8	1.6
Ra-226 and decay products, 35% equilibrium	-	0.03
Ra-228 and decay products equilibrium	-	0.03
Po-210 and decay products 50% equilibrium	0.3	0.3
Rn-222 dissolved in tissues	0.3	0.3
External irradiation (excl. neutrons)	56-150	56-150
Terrestrial γ rays from building materials (measured inside of buildings)	17-180	17-180

TABLE 6 Average Exposure Due to Man-Made Sources of Radiation

	Genetically-Significant dose rate (mrad/yr)	Dose/exposure or treatment (mrad)	
Medical sources		Gonad	Bone Marrow
Diagnostic x-ray	7-58	0.1-5100	0.2-2000
External radiotherapy	2-13	0.1-160,000	0.5-100
Internal radioisotopes	0.2-0.4		
		Dose commitment/individual (mrad)	
Weapons test fallout (1954-1962 testing)		Gonad	Bone Marrow
To year 2000	2	80	140
After year 2000 (due to C-14		180	180
Occupational	0.2		
Miscellaneous (e.g., consumer products)	2		

TABLE 7

Predictions of World and U.S. Population Exposure Resulting From the Expected Release of Kr-85 and H-3 Formed During Operation of a 1000 MWe Reactor in 1980

Energy System	PWR	BWR	HTGR
World (whole body man-rad)			
Kr-85	130	130	256
H-3	22	21	21
Total	152	151	277
U.S. only (whole body man-rad)			
Kr-85	6.1	6.1	12.0
H-3	2.4	2.3	2.3
Total	8.5	8.4	14.3

Note: The predictions of the global model are order of magnitude estimates. The number of significant digits shown is not indicative of precision.
(Hub, 1973)

TABLE 8

Global Model Predictions of World and U.S. Population Expsoure Resulting From the Expected Release of Kr-85 and H-3 Formed During Operation of a 1000 MWe Reactor in 1990

	PWR	LMFBR
World (whole body man-rad)		
Kr-85	0.55	0.39
H-3	29	31
Total	30	31
U.S. (shole body man-rad)		
Kr-85	0.02	0.02
H-3	2.7	2.9
Total	2.7	2.9

Note: The predictions of the global model are order of magnitude estimates. The number of significant digits shown is not indicative of precision.
(Hub, 1973)

TABLE 9

Radiation Dose From Nuclear Energy Systems

Energy System	1980 PWR	1980 BWR	1980 HTGR	1990 PWR	1990 LMFBR
General Population					
Global model (man-rad)*	150	150	280	30	31
Local model (man-rad)	4	25	5	4	4
Occupational Personnel					
Miners' exposure (man-WLM)	110	100	58	110	0
All other fuel cycle steps (man-rad)	345	350	327	345	339

Man-rad population doses are whole body doses.

WLM (Working Level Months) is the unit of miner exposure used in uranium mining.

of risk from radiation exposure are often found in this category. Table 10 gives such a risk summary. Other somatic effects include reduced fertility and reduced lifespan.

Several factors may be similar between fossil and fission power plants such as thermal pollution. Thermal discharges from nuclear plants are relatively higher than for fossil plants due to lower thermal efficiency. Particulate emission is essentially zero for a nuclear plant, although quite large for a fossil plant.

The dollar cost of social impact from operation of a nuclear power plant has been estimated in the Argonne study[25], and values can be compared to the fossil plant costs notes earlier. For a 1000 MWe plant operating in 1990 the annual external costs were estimated to be $1,100,000 for a light water reactor plant and $900,000 for a LMFBR. As with the fossil plant the largest fraction of the cost was due to thermal discharge. These costs were higher than the fossil plant and were $1,000,000 and $800,000 for the LWR and LMFBR respectively. The total health related effects in terms of man-days lost is 1790 for the LWR and 1310 for the LMFBR. A more detailed breakdown of the Argonne results with comparison to the fossil plant is given in Table 11.

TABLE 10

Summary of Risk of Radiation Induced Somatic and Genetic Effect

Somatic

Estimates of the probability that a person will develop a malignant neoplasm following irradiation in various periods of life.

Type of Neoplasm	Period of Life at Time of Irradiation	Probability of Developing Malignancy During Time Period Specified	Exposure Condition to Which Probability Applies
Leukemia	Adulthood	Lifetime: $0(2 \times 10^{-5}/\text{rad})$[a]	Approximately uniform irradiation of red bone marrow.
Thyroid cancer	Infancy (< 6 months)	Lifetime: $0(10 \times 10^{-5}/\text{rad})$	Approximately uniform irradiation of thyroid. Not applicable to I-131 uptake by thyroid.
	Adulthood	Lifetime: $0(3 \times 10^{-5}/\text{rad})$	
Total Malignancies (including leukemia)	Adulthood In utero	Lifetime: $0(20 \times 10^{-5}/\text{rad})$ Before age 10: $0(60 \times 10^{-5}/\text{rad})$	Approximately uniform irradiation of whole body.

Genetic

Estimates of the probability that a mutation will be transmitted to a conceived offspring as a result of irradiation of a parent.

Period of Life at Time of Irradiation	Sex of Parent	Probability That Mutation is Transmitted	Exposure Condition to Which Probability Applies
Before end of reproductive lifetime	male female	$0(2 \times 10^{-3}/\text{rad})$[b] $0(0/\text{rad})$[b]	Approximately uniform irradiation of gonads.

[a]The notation of 0(r) indicates that r is an order-of-magnitude value

[b]Male and female are assumed to be equally irradiated, the situation which is encountered in exposure of the general population. If female alone is irradiated, then the estimate of zero transmitted mutations should not be applied.

(Hub, 1973)

TABLE 11

Annual Costs for 1000 MWe Energy Systems for Nominal 1990

$ = Millions of dollars
MDL = Man-days lost

Item / Energy System		PWR $	PWR MDL	Coal $	Coal MDL
INTERNAL COSTS					
Conventional Costs					
Capital		80		50	
Operation & Maintenance		9		14	
Fuel		21		74	
Health & Accident					
Occupational Accident		C	490	C	2400
Occupational Health		C	240		~0
Public Injuries in Transportation		C	30		S
Total Internal		110	760	138	2400
EXTERNAL COSTS					
Public Health & Accidents					
Routine Pollutant Release		.003	40		U
Accidental Radiation Release		S	S		–
Large Accident at Power Plant		–	U		–
Transportation Accidents		.002	30		S
Genetic Effects		.006	70		U
Occupational Health & Accidents					
Accidents		.04	490	0.2	2400
Health		.02	240		~0
Genetic Effects		.07	920		U
Damage					
Water Base	Thermal Discharge	1.0		0.7	
	Other				
Air Base	SO_2 & Particulates	0.		S	
	Other				
Land Base	Mining			~0	
Total External Man-Days Lost			1790		2400
Total External Cost		1.1		0.9	
Total Internal & External MDL (Rounded)			2600		4800
Total Internal & External Cost (Rounded)		111		139	

S = Small
U = Unevaluated
C = Included in conventional cost

NUCLEAR POWER ECONOMICS

Energy cost can be broken into three components:

1) investment costs

2) fuel costs

3) operating and maintenance costs

An additional cost, the social cost, is discussed in the previous section. A major justification for the nuclear fuel industry is the low nuclear fuel cycle cost. The calculation of the nuclear fuel costs involves the cost of each unit operation in the nuclear fuel cycle and also the schedule, since carrying charges must be accounted for. Fuel cycle costs can be calculated by simplified hand techniques[27-31] or more complex computer programs.[32-35]

Table 12 lists the results of a typical calculation.[2]

TABLE 12[2]

PWR Fuel Cycle Cost Projection
1,150 MWe
1975 Startup
80% Capacity Factor

	Fuel Cost (mills/kwh)			
	Consumption Costs	Financing Costs	Total	% of Costs
Fabrication (@ $70/kg U)	0.34	0.08	0.42	20
Uranium Ore (@ $8/lb U_3O_8)	0.56	0.18	0.74	36
Conversion (@ $2.52/kg U) and reprocessing (@ $45/kg U)	0.62	0.16	0.78	37
Spent fuel shipping and reprocessing (@ $45/kg U)	0.19	−0.04	0.15	7
Plutonium (@ $7.50/gm Pu) and uranium credits	−0.35	0.08	−0.27	—
Totals	1.36	0.46	1.82	100

Notes: Consumption costs include interest during construction in the first core. Cost of money and interest during construction at 7%/yr and total fixed charge rate on non-depreciable capital at 14%/yr. The first three items include 4% sales tax.

The cost of power plants, nuclear and fossil, has been increasing.[37,38] This trend can be expected to continue. In general the nuclear plant costs more than the fossil plant, but the lower fuel costs for the nuclear make the nuclear plant competitive, depending on the price of coal. Table 13 also taken from reference 2 gives an estimate of energy cost for a typical nuclear plant.

TABLE 13[2]

Estimates of Energy Costs
(mills/kwh)

	1975 LWR
Investment costs	4.0-4.8
Fuel costs	1.7-1.9
Operating and maintenance costs	0.3
Total energy costs	6.0-7.0

The use of a plant in a power network depends, of course, on the other power plants available, the characteristics of each plant, incremental power costs of each unit, and the power demand on the system. In case of the outage for nuclear refueling, other units must be committed and dispatched (or power purchased from the outside) to meet the demand. The cost of nuclear power is system dependent. According to Hoskin[3]

> "The strong interdependence between management of nuclear fuel and overall power system management leads to a very large and complex multi-stage optimization problem which can best be treated, in principal, by the systematic application of simulation, systems analysis, and operations research techniques. Over the past four or five years a great deal of work has been done on various approaches to and various aspects of this or closely related optimization problems. Some products of these efforts are now in routine use, others are approaching the power of moving from the development stage to practical application, while some are still in the formative and experimental stage."

Table 14[36] is a comparison of important characteristics of types of electric generating units, which must be considered for optimizing the mix of types of power plants in a system.

TABLE 14

CHARACTERISTICS OF TYPES OF ELECTRIC GENERATING UNITS

TABLE 1

CHARACTERISTICS OF TYPES OF ELECTRIC GENERATING UNITS

	Dimensions	Nuclear Steam (LWR)	Fossil Steam	Fast-Start Peaking	Hydro	Pumped-Hydro
System use		Base-load	Base-load and cyclical	Peaking	Inventory dependent	Peaking
Capacity factor	Percent	60-90	30-90	Up to 20	Up to 100	Up to 50
Capital cost	$/kwe	300-450	250-400	100-150	300-500	100-200
Unit capacity	MW	500-1200	200-1200	10-50	10-600	50-400
Minimum power	% unit capacity	10-40	10-50	75-90	0-10	25-40
Avg heat rate	MBTU/MWH	10.5-11	8.5-14	12-17	N/A	N/A
Avg net energy conversion efficiency	Percent	31-34	25-40	20-28	85-93	65-80
Fuel cost	¢/MBTU	16-20	35-80 (coal) 50-100 (oil)	50-100	0	Cost of pumping power
Energy cost	$/MWH	1.7-2.2	3.0-8.4	6.5-20	0	~1.5 x pumping power cost
Comments on fuel inventory		Depends on fuel cycle	Approximately constant at 100 days supply	4-8 hours (oil)	Depends on season	Depends on operating cycle
Transmission losses	Percent	Up to 10	Up to 10	Up to 5	Up to 10	Up to 15
Startup shutdown heat requirement	MBTU/MW Capacity	3-6	3-8	0-2	~0	~0
Min shutdown time	Hours	<2	2-10	<0.3	<0.5	<0.5
Maintenance requirement	Weeks/year	4-8 wk/ refueling	3-5	1-4	1-2	1-2
Forced-outage rate	Percent	Up to 15	Up to 20	Up to 40	Up to 5	Up to 10
Performance probability	Percent	85-100	80-100	90-100	95-100	95-100

PLUTONIUM RECYCLE IN LIGHT WATER REACTORS

According to Graph 12 page 27 of this report, by 1976 plutonium will be discharged from operating power plants at a rate of about 14,000 kilograms of fissile material per year with a total worth of over 100 million dollars. In 1978 the production rate will be 25,140 kilograms of fissile material per year. The cumulative value of plutonium produced in the next ten years is approximately 200,000 kg. It is apparent that there will be a strong economic incentive for recycling plutonium in thermal reactors in the United States in the mid-1970's to mid-1980's.

The concept of plutonium recycle has been with the nuclear industry for a long time because the nuclear fuel cycle economics depends upon how well the plutonium generated by thermal reactors can be utilized. The credit for plutonium has a potential value of more than 10% of the fuel costs of the lightwater reactors now committed. But that plutonium must be recycled economically for this credit to be achieved. Nuclear fuel costs analyses have taken into account the credit for plutonium since the 1950's and today's light water reactors receive a plutonium credit of about .2 mil/kil hr. This value had been supported in the United States by the Atomic Energy Commission's guaranteed buy-back, which had been used to supply various research and development requirements in providing for demonstration programs. In December 1970 the guaranteed government buy-back of plutonium ended. So that as more reactors come on the line in the 70's, substantial quantities of plutonium over and above any requirements for breeder development will become available.

It is presently estimated that the first large scale commercial breeder reactor will not be able to go on the line until during the mid-1980's. If so, the requirements for fast breeder inventories would not become a substantial factor in the plutonium market before the 1990's. Without plutonium recycle by 1984, many tons of fissile plutonium would accumulate, which would amount to well over one billion dollars. It would be uneconomical of course to stock pile large amounts of plutonium for an extended period of time.

It should be pointed out that we are producing and burning plutonium in place in current day reactors since as much as 40% of the energy is produced by the plutonium in the core after 30,000 megawatt days per metric ton of uranium. Although the economic importance of plutonium recycle starting in the mid-70's has been generally recognized, the preparations and the development programs required for the necessary recycle ability are not as fully appreciated. There are several important differences between plutonium and uranium fuel that require careful design consideration. The plutonium, which is produced in a reactor consists of several isotopes. Important characteristics of these isotopes are listed in Table 15. Unlike uranium fuel, for example as shown in the table, the designer must work with plutonium that is 71% fissile, the remainder being nuclear poison. As shown by Puechl[39] the details of nuclear analysis to calculate the depletion of the higher isotopes must be accounted for and since they affect the reactivity lifetime in an important fashion. The designer must account then for the product buildup that has taken place after the material is being recycled.

There are significant nuclear differences in the characteristics between plutonium and uranium. These characteristics are summarized in Table 16. Some characteristics for the mixed oxide PuO_2UO_2 reactor are worth mentioning.

TABLE 15. Characteristics of PWR-Grade Plutonium

			Major Radiation Sources for		
Isotope	Fraction*	Fissile	Alpha	X, Gamma	Neutron
Pu^{238}	< 0.01				X
Pu^{239}	0.58	X	X		
Pu^{240}	0.23		X		X
Pu^{241}	0.13	X		X	
Pu^{242}	0.06		X		X
Am^{241}	**			X	
U^{237}	**			X	

* Based on recycling plutonium generated after 3 cycles of operation in a large PWR.

** Daughter products of ^{241}Pu which has a 13 year half life.

TABLE 16. Capsule Comparison of Uranium and Plutonium Nuclear Design Characteristics

Parameter	Plutonium Core	Reason for Difference	Consequence
Moderator Temperature Coefficient	More Negative	Increased resonance absorption and spectrum shift	Improved stability and transient characteristics except for steam break
Doppler Coefficient	More Negative	Pu-240 resonances	Improved transient characteristics
Cold-to-Hot Reactivity Swing	Increased	Larger moderator temperature coefficient	None-boron used for compensation
Installed Reactivity	Reduced	Reduced depletion rate-Reactivity saturates	None
Control Rod Requirement	Increased	Larger moderator and doppler coefficients	Possible increase in number of rods
Control Rod Worth	Reduced	Thermal flux reduced	Possible increase in number of rods
Boron Worth	Reduced	Thermal flux reduced	None
Xenon Worth	Reduced	Thermal flux reduced	Improved stability
Fission Product Poisons	Increased	Increased yields-Increased resonance absorptions	Reactivity penalty
Local Power Peaking	Increased	Increased water worth	Fuel management action required
Delayed Neutron Fraction	Reduced	$\beta_{pu} < \beta_u$	Rod ejection accident

Qualifications: 1. Effects can be modified by changes in design H/F; 2. Successive recycles influence the parameters

The temperature and Doppler coefficient are both more negative in the partial plutonium core. However, the former results in improved stability and the latter in imporved transient response. Xenon worth is also decreased resulting in improved stability of the thermal reactor. On the negative side, however, the fission products increase, resulting in reactivity penalty. Local power peaking also becomes a problem, but this can sometimes be solved by certain fuel management requirements. Also control rod worth decreases result in a necessity for more control rods.

Another deviation from a uranium experience involves an enriching step accomplished in the plutonium fuel fabrication plant. For the uranium fuel fabricated this function is provided by the AEC. Fuel fabrication is another important problem area in developing plutonium recycle capability. A number of problems unique to plutonium are not encountered during uranium fabrication. These differences from uranium fabrication include toxicity, radiation and criticality considerations, all of which affect the development of the required fuel facilities.

Because of its toxicity, plutonium must at all times be isolated from the personnel until the product is encapsulated. It is therefore necessary that it be confined by effective barriers such a glove boxes which completely contain the processing equipment. Directionally controlled air flow is needed to limit the spread of airborne contaminants.

Shielding is another problem for plutonium recycle fabrication. Neutron and gamma radiation from the plutonium isotopes, as summarized in Table 15, constitute sources of external exposure when handling plutonium. The magnitude of the gamma radiation from the american depends on the time between reprocessing and fabrication. Neutron radiation levels depend on the fuel burnup and the recycle history of the plutonium. Criticality safety is another important aspect in which plutonium processing is different from uranium processing. Much of the fabrication process plutonium enrichment is equivalent to 93% enriched uranium. This high enrichment means that small batches are required for those parts of the process which involve undiluted plutonium. By contrast the maximum uranium enrichment employed in fabricating uranium fuel is of the order of 3%. Still another basic problem in developing plutonium recycle capabilities will concern licensing. Different licensing criteria for the AEC, Department of Transportation, and IAEA have to be satisfied regarding toxicity, radiation, nuclear considerations, and safeguards. For example the plutonium plant must meet different licensing criteria than a similar uranium facility. Also new licenses will be required for the containers which are needed to ship the fabricated fuel to the reactor site. It would not be suprising if they were intervenor groups which would delay or prevent licensing for the use of plutonium recycle.

The introduction and success of the fast reactor may actually result in short lived LWR plutonium recycle programs as power requirements will be filled by fast reactors which breed their own fuel which may be plutonium if the fertile complement is uranium. Hence, plutonium fuel requirements may be restricted to operating lightwater reactors. Plutonium requirements for recycle will possibly peak around 1990-1995, assuming of course, that breeder reactors are being ordered in the early or mid-1980's. There have been a number of programs sponsored by the AEC and by the Edison Electric Institute to study the characteristics of plutonium needed for recycle. The overall plutonium recycle program which started in 1964 included 4 years of operation and post irradiation examination of Saxton plutonium fuel, two joint projects with the Edison Institute, and the criticality studies for the Empire State Atomic Development Association. It also included operation of a Westinghouse fuel development laboratory which was completed in 1969. Further data are listed in Reference 40.

CURRENT DESIGN PARAMETERS OF THE VARIOUS CONCEPTS OF NUCLEAR POWER PLANTS

(This section was prepared by Dr. R. A. Karam, Associate Professor of Nuclear Engineering, Georgia Institute of Technology.)

Table 17 summarizes the pertinent design parameters of the PWR, BWR, HTGR, LMFBR, and GCFR. In terms of plant efficiency, the LMFBR and the gas cooled reactors, i.e., the HTGR and GCFR, are superior to the water reactors. The main reason for this is the higher steam-cycle temperatures. Thermal pollution from the LMFBR and gas-cooled reactors is lower than the water reactors, due to better thermal efficiency.

The power density in the the LMFBR is about an order of magnitude larger than the thermal reactors and almost a factor of 2 larger than the GCFR. The equilibrium condition for fission product accumulation is not well established in fast reactors. However, it is safe to say that the conversion of fission products through neutron absorption is significantly lower in fast reactors than it is in thermal reactors.

17. CURRENT DESIGN PARAMETERS OF THE VARIOUS CONCEPTS OF NUCLEAR POWER PLANTS

	PWR	BWR	HTGR	LMFBR	GCFR
A. GENERAL					
PLANT	OCONEE	BROWNS FERRY	PHILADELPHIA ELEC.		GULF GENERAL
MANUFACTURER	BABCOCK & WILCOX	GENERAL ELECTRIC	GULF GENERAL ATOMIC	GENERAL ELECTRIC	ATOMIC
OUTPUT	2584 MW(t) 922 MW(e)	3293 MW(t) 1098 MW(e)	3000 MW(t) 1174 MW(e)	2500 MW(t) 1000 MW(e)	1093 MW(t) 420 MW(e)
EFFICIENCY	34.5%	33.3%	39.1%	40%	38.4%

17 CURRENT DESIGN PARAMETERS OF THE VARIOUS CONCEPTS OF NUCLEAR POWER PLANTS

	PWR	BWR	HTGR	LMFBR	GCFR
B. OPERATING CHARACTERISTICS					
FUEL T	$FUEL_{max}$ 4250°F $CLAD_{max}$ 653°F	$FUEL_{max}$ 4380°F $FUEL_{avg}$ 1100°F	$FUEL_{max}$ 4400°F $FUEL_{avg}$ 1634°F	$FUEL_{max}$ 4340°F $FUEL_{avg}$ 2670°F	
COOLANT T	INLET 554°F OUTLET 604°F	376.1°F 562 °F	INLET 606°F OUTLET 1366°F $\Big\}$ He	INLET 800°F OUTLET 1100°F	INLET 470°F OUTLET 1112°F
PRESSURE	COOLANT 2200 psig	1000 psia operating	710 psig; Δp=10 psig	~ 100 psi Δp=66.5 psig	1000 psia (He) Δp=32.6 psig
STEAM	572°F @ 910 psig	562°F @ 1146	1000°F @ 1450 psi	1000°F @ 3500 psia	~ 1000°F @ ~ 1400 psi

17 CURRENT DESIGN PARAMETERS OF THE VARIOUS CONCEPTS OF NUCLEAR POWER PLANTS

	PWR	BWR	HTGR	LMFBR	GCFR
C. CORE PARAMETERS					
POWER DEN.	84.1 kw/ℓ	50.8 kw/ℓ	8.4 kw/ℓ	~ 500 kw/ℓ	218.6 kw/ℓ
PEAKING FAC	1.011	2.6	1.6	1.94	---
DOPPLER COEFFICIENT	-2.0×10^{-5} to -3.1×10^{-5} $\Delta k/k/°C$	-2.3×10^{-5} $\Delta k/k/°C$	\$ $-2 \times 10^{-5}/°C$	$-1.0 \times 10^{-5}/°C$	$-1.0 \times 10^{-5}/°C$
VOID COEFFICIENT	$+1.8 \times 10^{-4}$ to -5.4×10^{-3} $\Delta k/k/°C$	-1.8×10^{-3} to -2.9×10^{-3} $\Delta k/k/°C$	(- SMALL ?)	+ \$ 2.5 CORE ONLY + \$ 4.25 MAXIMUM	$+1.8 \times 10^{-6}/°K$
TEMPERATURE COEFFICIENT	FUEL---2.0 to -3.0×10^{-3} % $\Delta k/k/°C$ CLAD--0 to -5.4×10^{-2} % $\Delta k/k/°C$	-9.0×10^{-5} $\Delta k/k/°C$	$-9.30 \times 10^{-5}/°C$ at 300°K $-3.3 \times 10^{-5}/°C$ at 1100°K		
NEUTRON LIFETIME	1.6×10^{-5} sec	~ 1×10^{-4} sec	3.4×10^{-4} sec	~ 5×10^{-6} sec	4.37×10^{-7} sec
DELAYED N FRACTION	.0072	~ .007	~ .007	~ .0035	~ 0.0035

17 CURRENT DESIGN PARAMETERS OF THE VARIOUS CONCEPTS OF NUCLEAR POWER PLANTS

	PWR	BWR	HTGR	LMFBR	GCFR
D. FUEL					
COMP.	UO_2 SINTERED PELLETS	UO_2	U:Th COATED PARTICLES	PuO_2 + UO_2 MIXED OXIDES	PuO_2 + UO_2 MIXED OXIDES
ENRICHMENT (%)	3 ZONES: 2.05, 2.10, 2.15	2.19%	93%	17.9% (INITIAL)	
PINS	CLAD--ZIRCALOY-4 O.D. 0.430"	CLAD--ZIRCALOY-2 O.D. 0.562"	O.D. 0.619"	SS-316 CLAD O.D. 0.245"	STAINLESS STEEL OR HASTELLOY CLAD O.D. 0.439"
ASSEMBLY	208 RODS [15 x 15 array](less 17 positions for control)	7 x 7 ROD ARRAY	132 RODS	282 SUBASSEMBLY	100 RODS PER BOX (5.2" square)
TOTAL	177 ASSEMBLIES 207, 486 lb UO_2	764 ASSEMBLIES 327, 571 lb UO_2	3486 lb U 82,500 lb Th	121,000 FUEL PINS 4910 lb CORE 192 lb BLANKET	21,300 RODS (100 boxes) FISSILE LOADING 3894 lb

17. CURRENT DESIGN PARAMETERS OF THE VARIOUS CONCEPTS OF NUCLEAR POWER PLANTS

	PWR	BWR	HTGR	LMFBR	GCFR
E. CONTROL					
	5% Cd, 15% In, 80% Ag	SS CLAD B_4C	INCOLOY 800 CLAD	SCRAM	SS CLAD B_4C
	RODS--SS 340 CLAD	185 CRUCIFORM RODS 144" LONG	B_4C/GRAPHITE	32 RODS B_4C	29 RODS
	69 ASSEMBLIES		73 ROD PAIRS		
	16 RODS/ASSEMBLY	TEMPORARY CURTAINS	EMERGENCY SHUTDOWN	SHIM	
	POISON LENGTH 134"	STAINLESS STEEL w/5700 ppm B;	B_4C/GRAPHITE	32 RODS B_4C	
	B-10 in H_2O TEMPORARY POISON	356 SHEETS BETWEEN FUEL CHANNELS	73 CANNISTERS		

17 CURRENT DESIGN PARAMETERS OF THE VARIOUS CONCEPTS OF NUCLEAR POWER PLANTS

	PWR	BWR	HTGR	LMFBR	GCFR
F. STRUCTURE					
	PRESSURE VESSEL SS CLAD CARBON STEEL CYLINDER ID 14.3' h 37.4' DESIGN PRESSURE 2500 psig	PRESSURE VESSEL STAINLESS STEEL CARBON STEEL CYL ID 20.9' h 72.6' DESIGN PRESSURE 1000 psia	PRESTRESSED CON- CRETE REACTOR VESSEL (PCRV) ID 37' IH 47.3' OD 100' OH 91.5' DESIGN PRESSURE 765 psig	PRESSURE VESSEL CORE d = 11.5' h = 16" STEEL MAIN Na TANK d = 52' x 1" THICK h = 47' DESIGN PRESSURE 10 psig (NO TANK)	d_{core} 7.65' $d_{blanket}$ 10.7' L/D RATIO 0.5 PRESTRESSED CON- CRETE CYLINDER w/FLAT ENDS LINED WITH STEEL

17 CURRENT DESIGN PARAMETERS OF THE VARIOUS CONCEPTS OF NUCLEAR POWER PLANTS

	PWR	BWR	HTGR	LMFBR	GCFR
G. CONTAINMENT					
	PRESTRESSED CONCRETE CYLINDER	REINFORCED CONCRETE SS LINED			
	ID 116'				
	h 208.5'				
	DESIGN PRESSURE	DESIGN PRESSURE	DESIGN PRESSURE	DESIGN PRESSURE	DESIGN PRESSURE
	58 psig	62 psig		----	----

17 CURRENT DESIGN PARAMETERS OF THE VARIOUS CONCEPTS OF NUCLEAR POWER PLANTS

	PWR	BWR	HTGR	LMFBR	GCFR
REFERENCES FOR DATA IN THIS SECTION	OCONEE	BROWNS FERRY	GGA DESIGN	G.E. DESIGN	G.E. DESIGN
	"Nuc. Engr. Int'l" Apr 70 15:337-344 World's Reactors #50	Nuclear Energy Conversion, M. M. Wahil Intext Educational Publs. 1971, p. 114 (table)	HTGR Fact Sheet Gulf Oil Corp. 1973	Argonne National Laboratory ANL 7120 Proceedings of the Conference on Safety, Fuels, and Core Design in Large Fast Power Reactors October 11-14, 1965	
	USAEC DOCKET 50269-1 "Preliminary Safety Analysis Report" Duke Power Co. 1 Dec '66	USAEC DOCKET 50259-1 "Design & Analysis Report" (TVA) 7 July '66		p. 185 1000 MW(e) Fast Sodium Cooled Reactor Design Cohen & O'Neill General Electric	p. 230 Safety Characteristics of Large Gas Cooled Fast Power Reactors Fortesque et al. General Atomic
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FINAL REPORT

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COMPARATIVE EVALUATION OF SOLAR, FISSION, FUSION, AND FOSSIL ENERGY RESOURCES

PART III

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TABLE OF CONTENTS

NUCLEAR FUSION POWER

INTRODUCTION

In the preceding section, the role of nuclear fission reactors in becoming an important power source in the world was discussed. Oil and petroleum could last another hundred years or so, breeders a few more thousand years, but fusion power is our only hope for the very long range. Unless we develop breeder reactors, the supply of fissile nuclear fuel will be severely depleted by the year 2000. With breeder reactors the world supply of uranium could last thousands of years. However, breeder reactors have problems of a large radioactive inventory and an accident potential which could present an unacceptable hazard. Although breeder reactors afford a possible solution to the energy shortage, their ultimate role will depend on demonstrated safety and acceptable risks and environmental effects. Fusion power would also be a long range, essentially permanent, solution to the world's energy problem. Fusion appears to compare favorably with breeders in safety and environmental effects. If the fast breeder program is successful, power could be produced by breeders in the mid-80's or so. A controlled fusion reactor is a competitor with the breeder reactor in solving our long range energy needs. However, the possibility of achieving controlled fusion reactors and the developmental time span is speculative.

Controlled fusion research has developed world-wide for the past twenty years. Fusion was a classified field of research in the early 1950's when very little was known about its root science, the physics of high temperature plasmas. The fusion program was declassified in 1958 and by the early 1960's scientific problems relative to controlled thermonuclear research were identified and a systematic study was undertaken.

The motivation for achieving controlled fusion power has remained essentially the same from the beginning. Nature has made available a virtually inexhaustable source of near zero cost fuel in the deuterium contained in the world's oceans. It also appears that the generation of fusion power may have little hazard and minimal adverse environmental effects. The United States has plentiful deuterium and lithium resources and would be independent of foreign sources for power. Fusion reactors do not utilize fissionable materials which might be subjected to diversion for military purposes. A strong fusion reactor industry would strengthen the country's technological base, and the foreign sales of fusion reactors could have a favorable effect on the balance of trade.

R. F. Post,[1] head of the magnetic mirror program at Lawrence Livermore Laboratory and a long time proponent of nuclear fusion, presented an "Optimist's Fusion Power Timetable" (See Figure 1) which is useful in relative terms. Writing from a more moderate position, R. G. Mills[2], head of the Engineering and Development Division of Princeton University's Plasma Physics Laboratory, stated:

> "Lest we forget, it has not yet been proved that a controlled thermonuclear reactor is possible. If closed geometries fail, mirrors may succeed. If mirrors fail, too, perhaps pulsed devices or the Astron will be possible. If all magnetic confinement fails, laser-ignited microbombs may carry the day, or even minibombs in underground cavities. If none of these schemes is economically feasible, then fission breeder reactors will have the full responsibility for fueling the future of mankind.
>
> Closing on this cautionary note, however, should not mask the fact that today, in contrast to the situation a few years ago, a majority of scientists and engineers knowledgeable in the field of controlled thermonuclear research believe that fusion power will be possible and will become practical in this century."

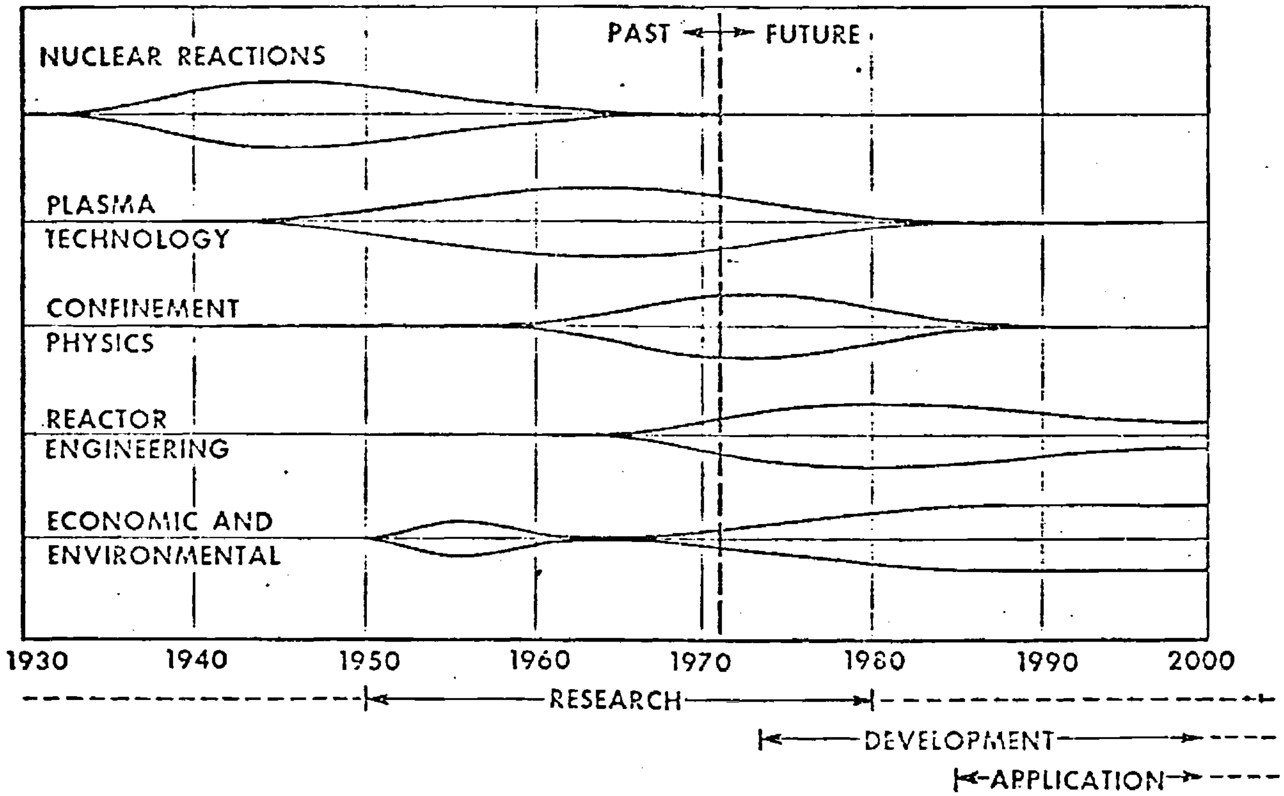

Figure 1. "Optimist's Fusion Power Timetable"

Source: Ref. 1

In 1971 and 1972 national concern over future energy sources deepened. The House of Representatives' Subcommittee on Science, Research, and Development, chaired by John W. Davis of Georgia, convened a Task Force on Energy. The Task Force, headed by Mike McCormack, issued its report in December, 1972. With regard to controlled fusion the report stated:

"One perplexing question for planners of national energy policy is what weight to give to the prospects for a practicable controlled thermonuclear reaction, or fusion of hydrogen atoms. Scientists are confident that they know and understand the conditions in which isotopes of hydrogen will fuse together with a release of energy. The existence of the hydrogen bomb is convincing proof that an uncontrolled thermonuclear reaction is possible. But after some 20 years of expensive research and experimentation, scientists still do not know whether it will ever be possible to get useful energy from a controlled thermonuclear process. The potential fuels for such a process are deuterium and tritium. The former exists in nature where it constitutes one part of 6,500 in the hydrogen in water. The latter is made from a lithium isotope by exposing that material to neutrons. The lithium 6 isotope constitutes 7.5 percent of natural lithium. So in essence, the fuels for fusion power would be natural deuterium and transformed lithium.

The first fusion reactions likely to be achieved would use both deuterium and tritium. Later it may be possible to sustain a reaction with deuterium alone. If fusion research and development is unable to go beyond the first process, then fusion's value as a major new fuel resource will be determined by the amount of lithium in nature. Professor Manson Benedict of MIT estimates that the deuterium-tritium process would add to U.S. energy reserves 100×10^{18} Btu, or about one-tenth of the energy resource he estimates would be available from uranium and thorium assuming that breeding is perfected. If scientists and engineers are able to produce the more demanding physical conditions required to use deuterium alone as a fusion fuel, then deuterium could represent a virtually inexhaustible supply of energy. Benedict estimates successful commercial use of deuterium as fusion fuel would expand world energy resources to over 17 billion $\times 10^{18}$ Btu, a truly limitless store of energy.

THE SITUATION IN 1964

Fusion was recognized by the Interdepartmental Group in 1964 as a potentially unlimited source of energy.[3] But, observed the group, before a self-sustaining reaction could be achieved, an enormous amount of further research in basic plasma physics was indicated. Financial support of basic research in fusion should be continued and increased not only because of the monumental potentialities of fusion power, but also because the fundamental knowledge secured would be invaluable to many peripheral energy fields. Of the anticipated advantages of fusion, the Group identified its limitlessness as a source of power and its inherent safety as major reasons to continue fusion research.

An immense effort would be needed with no promise of immediate returns in the immediate future. According to the Group:

> ....The task is immense, and there is no indication that it will be solved in the immediate future. Even if controlled fusion reactions can be achieved on a laboratory basis, it will take many years to develop an operable power generator.

THE SITUATION IN 1972

The outlook for fusion is somewhat brighter in 1972, but the scientific feasibility remains undemonstrated. Experiments in the Soviet Union with its Tokomak machine in the late 1960's revived hopes that the technical conditions for a useful controlled nuclear reaction could be achieved. This advance led to a flurry of experimental activity in the United States where some fusion research projects modified their machines to verify the reported results. More recently it has been proposed to heat the hydrogen isotopes to a temperature high enough to initiate fusion by use of a laser beam impinging upon a pellet of deuterium-tritium or deuterium to produce a burst of fusion energy.

Whether a controlled reaction can be reliably demonstrated remains speculative. Proponents of fusion expect such a demonstration within 10 or so years. However even the most optimistic of fusion advocates do not expect to see it in commercial use before the late 1990's. So barring an unexpected breakthrough, fusion will be of little importance as a useful energy source for the next few decades. If it can be achieved, then in principle, the enormous amounts of energy available would make it possible to substitute synthetic liquid and gaseous fuels for those obtained from coal, oil and gas.

For a controlled thermonuclear reaction to occur, it is necessary for engineers and scientists to find ways to raise the heat energy of heavy hydrogen molecules to from 100 million to 1 billion degrees Kelvin; to confine this hot ionized gas, or plasma for up to a second; and to maintain a certain minimum density of ions while doing so. At the same time fuel must be fed to the system and heat energy extracted from it for subsequent generation of electricity.

Many devices have been built throughout the world in attempts to achieve these critical conditions for fusion. On a world wide basis, over $150 million is being spent annually in fusion research. Japan, France, West Germany, Holland, Sweden, Italy, the United Kingdom, the Soviet Union and the United States each have fusion programs. Most of the research effort is carried on in the Soviet Union and in the United States which account respectively for 37 and 20 percent of the total fusion effort. Efforts in the United States have been carried out in some 40 universities, by several industrial groups, including the Texas Atomic Energy Research Foundation which is funded by electric utilities and at four major AEC funded laboratories - the Los Alamos Scientific Laboratory, the Lawrence Radiation Laboratory of the University of California, the Oak Ridge National Laboratory, and the Princeton Plasma Physics Laboratory.

Anticipatory design studies of a fusion reactor have inquired into environmental and safety factors. They suggest that fusion plants would not produce large quantities of radioactive waste, would be inherently safe against nuclear accident, and would discharge 50 to 70 percent less heat than existing steam-electric power plants. In addition, fusion theoretically offers possibility of direct conversion of heat energy into electricity through an MHD cycle."

In addition, the Task Force summarized the advice of experts in the field, including Herman Postma, then head of the Thermonuclear Division of Oak Ridge National Laboratory and presently Director of the Laboratory:

"Herman Postma of the Oak Ridge National Laboratory examined the technology, engineering, and environmental questions that will have to be faced once the scientific feasibility of fusion is demonstrated. Before fusion can be taken seriously as a possible source, he would carry the demonstration of scientific feasibility one step further to show that it is possible using real fuels -- deuterium and tritium -- to obtain more energy from a reaction than goes into producing that reaction. Though such an experiment might be small, it would show that the fusion process with real fuels occurs under actual working conditions and that a self-sustaining reaction would be possible.

Assuming that the scientific feasibility of fusion is demonstrated in the later 1970's or early 1980's, Postma outlines a series of intermediate steps toward the goal of economically useful fusion power. These are essentially the same as specified by Benedict. The first step is to design, construct, and operate an experimental power reactor to provide detailed engineering tests as well as understanding of dynamics of a plasma in a reactor. This reactor would not produce useful power. It might be built within 5 to 7 years after demonstration of scientific feasibility, depending upon the complexity and the results of the feasibility experiments.

The second stage would be to design, construct and operate prototype reactors. These would operate at higher power outputs, from 200 to 400 megawatts of thermal energy, and with power cycles designed to give reliable and continuous output. It may be necessary to operate such reactors for several years. From the time of conceptual design to the time of working demonstration could take as long as 10 years. At the end of that time, a substantial interest by industry would be expected. Successful operation of prototype fusion reactors would lead to the third stage: construction of demonstration fusion reactors of a size large enough to be commercially acceptable. These demonstration reactors would produce about 1000 megawatts of heat energy and would be operated to demonstrate reliability over long periods of time and to indicate the economics of commercial fusion power. The operation would allow vendors, utilities and the public to decide the usefulness of fusion power in terms of economic, physical, social and environmental conditions.

In summary, Postma postulates a sequential evolution of fusion research and development from the demonstration of scientific feasibility to that of commercial acceptability as taking at least 30 years beginning in the mid 1980's. The cost of this development and demonstration would likely be several billion dollars."

The question, "When fusion?" has been previously discussed by Rose[4] and Post[5] and by Gough and Eastlund.[6] The latter state:

"If fusion power is pursued as a 'national objective,' expanded programs could be carried out across the entire density range accompanied by parallel strong programs of research on the remaining engineering and materials problems to determine as quickly as possible the best routes to practical fusion power systems. Therefore, depending on one's underlying assumptions on the level of effort and the difficulties ahead, the time it would take to produce a large prototype reactor could range from as much as 50 years to as little as 10 years.

A recent budget proposal of the U.S. Atomic Energy Commission for fiscal years 1974, 1975, and 1979 is on an increasing scale: $145M, $250M, and $400M, respectively. On such a budget it is proposed to construct a scientific feasibility or physics test reactor in the early 1980's, a prototype power reactor in the late 1980's and a demonstration power reactor in the mid-1990's. Thus the A.E.C. forecasts availability of small amounts of fusion power in some twenty years. The subsequent rate of increase of fusion power availability would be determined by technological, economic, and social considerations. One technological consideration is the rate at which new tritium would become available for the startup of new reactors. Current estimates of tritium doubling time vary from a month to a year. Economic and social considerations will be conditioned by progress in the fast breeder program and by world energy demand some years hence.

BASIC PRINCIPLES

Nuclear Fusion Reactions

This section will serve only as a brief survey of basic principles. Most fusion reactors employ one or a combination of the following nuclear reactions:

Reaction Equation	Approximate Threshold Plasma Temperature
$D+T \rightarrow {}^4He$ (3.5 MeV) + n (14.1 MeV)	10 keV
$D+D \rightarrow {}^3He$ (0.82 MeV) + n (2.45 MeV); $D+D \rightarrow T$ (1.01 MeV) + p (3.02 MeV)	50 keV
$D+{}^3He \rightarrow {}^4He$ (3.6 MeV) + p (14.7 MeV)	100 keV

Each cycle requires an energy investment to initiate fusion, and each utilizes deuterium which occurs abundantly in nature and is available at low cost. The first reaction requires tritium which does not occur natrually and which therefore must be bred. The third reaction utilizes ^3He which can be obtained from DD reactions. All cycles involve emission of neutrons from the primary or secondary reactions (e.g., DD reactions in the D^3He cycle).

The DT Reaction

The DT reaction is considered most attractive for first generation fusion reactors because of its high energy gain and its low threshold temperature. The features of the reaction determine many of the basic characteristics of a DT fusion reactor.

1. Because about 80% of the energy output is carried by the neutrons, a special blanket of low atomic number materials will be required to convert neutron kinetic energy to thermal energy, as well as to provide a biological shield.

2. The blanket region of a DT reactor will become radioactive because nearly all materials become activated to some degree by energetic neutron bombardment. This activity will be minimized by appropriate materials choices.

3. DT reactors will work primarily on a thermal conversion cycle because neutron moderation gives rise to thermal energy.

4. Tritium must be bred. Neutron absorption in natural lithium appears attractive. Breeding ratios to 1.5 may be possible, giving doubling times of about a month. (A ratio of 1.3 appears typical.)

5. The elemental reaction product is inert helium.

6. There is some flexibility to deal with system losses and inefficiencies because the energy gain is high.

7. The DT cycle has the potential of being self-sustaining since the energetic charged fusion products (helium) can feed energy directly into the plasma.

The DD Reaction

Although the other cycles have lower energy gains, they have a number of attractive features. DD reactions utilize naturally occurring deuterium and hence do not require external tritium breeding, removing an important constraint from the blanket requirements. The reaction products (T and ^3He) are themselves fuel and will partially react with the deuterium before escape from the plasma. Unburned T and ^3He could be reinjected to improve the fractional burnup.

The D^3He Cycle

By increasing the operating temperature and reinjecting only the ^3He, the DD cycle can operate so that D^3He reactions contribute most of the output power, as little as 10% of the output being from DD neutrons (and its tritium by product). With efficient direct conversion of the energy from the charged D^3He reaction products, increased overall system efficiencies appear possible.

PHYSICAL CONDITIONS FOR FUSION

Temperature

Because the fuel nuclei are positively charged, high kinetic temperatures are required. Relative kinetic energies of the order 10 keV or larger are needed in order to overcome the mutual electrostatic repulsion of the fuel nuclei; these energies correspond to 100 million degree kinetic temperatures. The necessity of these high ignition temperatures is unavoidable. A large proportion of the effort to date has been directed at the attainment of these high temperatures. The highest temperature, to date, has been achieved in the magnetic mirror at the Lawrence Radiation Laboratory in the United States where ion temperatures of 6-10 keV are reported.

Plasma Confinement

It is necessary to isolate the fusion plasma from the surroundings. From the very beginning almost the entire effort in fusion research was devoted to the study of one particular approach to confinement, namely magnetic confinement. A magnetic field can confine a plasma by controlling the motion of its individual charge particles acting as a non-material means for insulating the plasma from the material walls of the chamber that shields it from the atmosphere. Magnetic confinement takes advantage of the fact that the fusion plasma is an almost ideal collisionless gas. A simple magnetic field seems an almost ideal container for fusion plasmas. Of course there is a problem in that a straight uniform field in a tube cannot prevent the confined plasma from dumping out of the ends. There are two basic forms

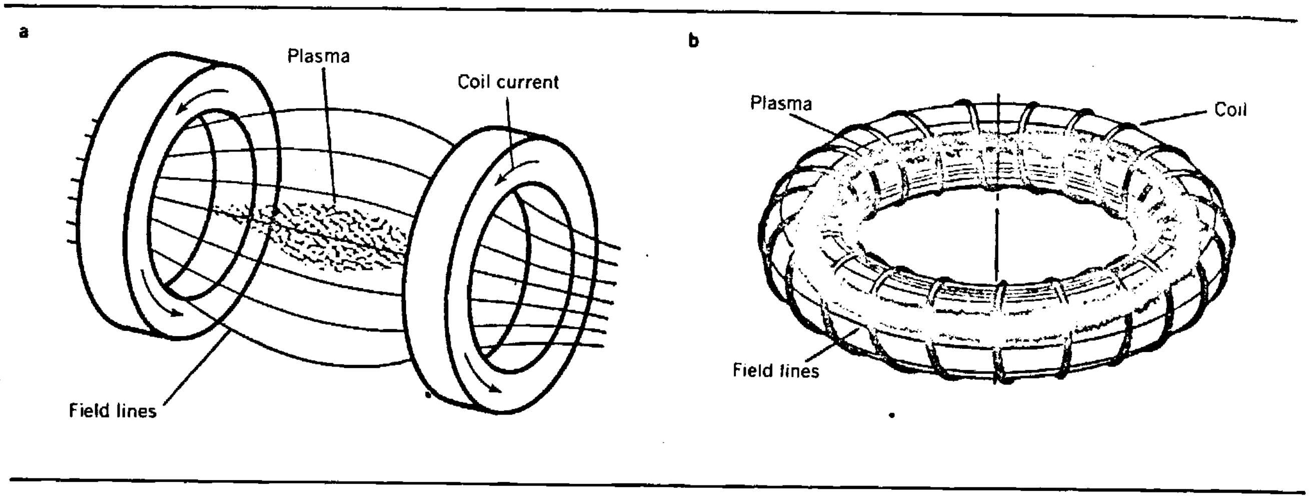

FIGURE 2.

Open and closed configurations for magnetic confinement of a plasma. Open (mirror) systems (a) use the repelling force that gyrating charged particles experience as they move into regions of increasing fields. Particles are trapped between the end "mirrors". In closed (toroidal) systems (b) particles course freely along the magnetic field lines, which are contained within a doughnut-shaped region. Diagram from R. F. Post, "Prospects for Fusion Power," Physics Today, April 1973.

of magnetic bottles: the "open" and "closed" geometries are utilized in a search for stable configuration. In the open system, as shown in Figure 2, the well-known magnetic mirror effect -- that is, the repelling force experienced by gyrating charged particles as they move into regions of increasing magnetic field -- is used to inhibit end losses. In the closed toroidal systems the particles course freely along the magnetic lines which are all contained within a doughnut shaped region. Various approaches involving particular reactor configurations will be discussed later.

More recently another approach to fusion has been proposed. It is the laser reactor idea, the newest one on the fusion scene. It is really the simplest one conceptually. In this concept tiny pellets of fusion fuel are irradiated by pulsed focused laser beams of nanosecond duration. These beams heat and densify the pellet interior, resulting in a burst of fusion energy. For densities which are envisioned, confinement is by means of inertia forces which confine the hot core in place for a sufficiently long time that no other confinement means is required.

Plasma Density

Two operating modes or regimes of fusion reactors are possible: 1) steady and 2) pulsed. In steady-state reactors which are limited to low power density by heat transfer and other considerations, a relatively narrow range of fuel density - about 10^{14}-10^{15} fuel ions per cubic centimeter - obtains. Higher densities involve a pulsed operation mode, up to and including micro-explosion modes such as those contemplated for laser irradiated pellets. The operating fuel density is dictated only by practical requirements. Fusion power densities vary as the square of the fuel density since each fusion reaction involves a collision of two reacting nuclei. At densities of approximately 10^{-5} of atmospheric density (corresponding to 3 times 10^{14} particles per cubic centimeter), power densities are as large as tens of megawatts per cubic meter and at atmospheric densities they would be 10^{10} times larger.

Confinement Times

Given an operating temperature, the fuel density would determine the power density. The requirements that the reaction be self-sustaining in turn defines a minimum average lifetime for the fuel ion. This is the time for the nuclear reactions to regenerate the energy invested in heating the fuel. The relevant quantity is $n\tau$, the product of density and confinement time. First criterion was published by J. D. Lawson in 1957[7]:

> "For a successful thermonuclear reactor not only does the temperature need to be sufficiently high, but also the reaction has to be sustained for a sufficient time. The reason for this is that the energy used to heat the gas is ultimately degraded to the temperature of the walls of the apparatus, and, consequently, sufficient thermonuclear energy must be released during each heating cycle to compensate for this degradation."

Lawson was the first to evaluate this important confinement parameter $n\tau$, the product of the plasma density and the confinement time. Mills[8] treated the situation further. Some of Mills' results are shown in Figure 3. Roughly, $n\tau$ must be greater than 10^{14} seconds per cubic centimeter, implying confinement times of between 0.1 and 1.0 seconds for a steady state reactor. For high density (pulsed systems) the time would be considerably shorter. Demonstration of the scientific feasibility of controlled thermonuclear fusion would require not only the achievement of the minimum fuel temperature but also a demonstration of the Lawson criterion.

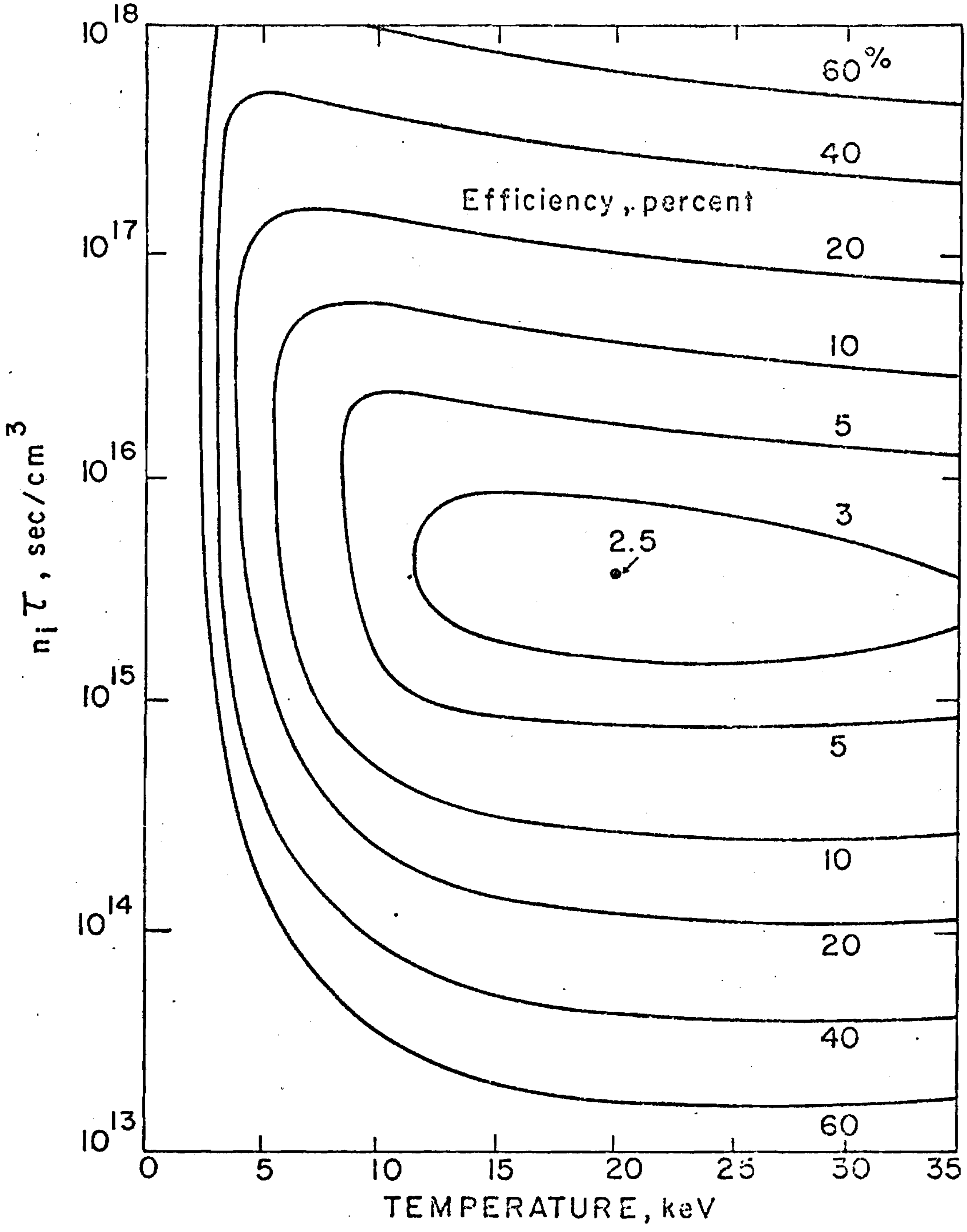

FIGURE 3. The Lawson Criterion and the Equilibrium Condition as a Function of Ion Temperature. Figure taken from R. G. Mills, Lecture Notes, Princeton University (1972).

THE WORLD FUSION EFFORT

In evaluating timetables for fusion development, it is useful to understand the balance of world effort in fusion research. The United States effort competes with extensive foreign programs in regard to international prestige. Moreover, owing to international recognition of the potential benefit of achieving fusion power, research results are shared through regular conferences such as those sponsored by the International Atomic Energy Agency. An estimate of the 1971 balance of research expenditures in controlled fusion research is shown in Figure 4, where it is noted that the U.S. contribution was only 16%. International developments have modified, and will continue to modify, the prospects for timely development of controlled fusion.

A recent development expected to bear on the question "When fusion?" is the decision by Euratom countries to begin design studies for a Joint European Tokamak (JET) device.[9] The present design team, headed by P. Rebut of Fontenay-aux-Roses, projects that JET will produce a plasma current of 3 megamperes, comparing with the present 230 kiloamperes record of the Soviet T-4 and French TFR devices, with 0.8 - 1.0 megamperes for the Soviet T-10 device scheduled for completion in 1975, and 1.6 megamperes for the Princeton Large Torus scheduled for completion also in 1975. Reactor conditions are expected to lie in the 10-20 megampere range.

The Japanese program presently holds the world record for plasma confinement in toroidal devices. The Japan Fusion Torus 2 (JFT-2) in March 1973 claimed an electron temperature of 700 eV and confinement time of 0.02 second[10]. An increase of magnetic field from 10 to 18 kilogauss by summer

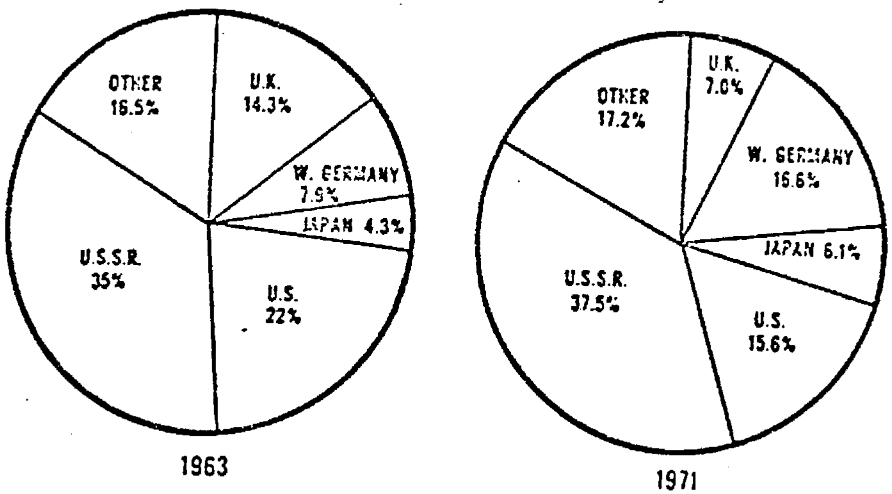

Figure 4. International Distribution of Fusion Effort.
Source: Joint Committee on Atomic Energy Hearings, 10-11 November 1971

of 1974 is expected to yield a confinement time of 0.05 to 0.07 second, and to raise the electron temperature to 1 keV.

SOVIET FUSION EFFORT

Soviet work on the concept of magnetic confinement for controlled thermonuclear reactions began at the Kurchatov Institute of Atomic Energy in Moscow in 1951. The first results of this work were reported at the Second International Conference on the Peaceful Uses of Atomic energy in Geneva in 1958. Subsequently the basic Soviet toroidal magnetic confinement concept has come to be known as the "Tokamak" concept. By 1964 four Tokamak installations had been completed. In 1968 a joint Soviet-British effort using the T-3 Tokamak demonstrated that plasma diffusion times in the Tokamak devices were considerably longer and thus better than the pessimistic results obtained previously with stellarator concepts. The latter gave the so-called Bohm diffusion time:

$$\tau_{Bohm} \sim \frac{10^{-2}\ r^2\ B}{T}$$

whereas the Tokamak results were between the Bohm diffusion time and the classical diffusion time

$$\tau_{DIF} \sim \frac{100\ r^2\ T^{3/2}}{\beta}$$

Subsequent developments have led to the so-called neoclassical theory of diffusion on which the scaling of Tokamak devices and reactor concepts is presently based. Record confinement parameters achieved with the T-3 were: $n = 3 \times 10^{13}$ to 5×10^{13} cm^{-3}, $\tau = 10$ to 15 msec, $T_e = 1.5 \times 10^3$ eV, and $T_i = 700$ eV. Since the 1969 international conference in Dubna, large and small Tokamaks have been installed throughout the world[11]. A complete review of this work is available.[12]

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* In these formulas T is in keV, B is in webers/M^2 and r is in meters.

Recently available in English translation are the forty-three Soviet papers presented at the Fourth International Conference on Plasma Physics and Controlled Fusion Research held in Madison, Wisconsin.[13] Fully described is theoretical and experimental work in pinch stabilization, Tokamaks (TO-1, T-4, T-6), plasma focus, laser, and electron-beam methods, plasma turbulence, open confinement systems (PR-6), closed confinements systems (TOR-1, L-1, Saturn-I, Uragan Stellarator) and high-frequency heating.

In addition to the Tokamak work at the Kurchatov Institute, stellarator work is being continued at the Physics and Engineering Institute of the Academy of Sciences of the Ukrainian SSR and the P. N. Lebedev Physics Institute of the USSR Academy of Sciences (FIAN). The comparative lack of success in previous U.S. and Soviet stellarator programs is now believed to result from a small poloidal magnetic field. In newly designed stellarator systems such as the Uragan-IM machine[14] confinement time is comparable to that of Tokamaks. Experiments at Culham and FIAN show near classical diffusion times.

The status of nuclear data for fusion reactor neutronics design has recently been addressed by Soviet workers at Kurchatov[15,16]. The Chernilin paper addressed the overall plan of a Soviet reactor concept based on the Tokamak, and discussed the nuclear materials requirements for the vacuum wall, tritium breeding blanket, coolant, supplementary neutron multipliers, moderator, and coil shielding. The nuclear data for lithium and niobium are reviewed in detail and graphs for the measured partial cross-sections of neutronics interest are presented against the British AWRE evaluation. It is concluded that while fission reactor requirements result in a firm data base from thermal to 5 MeV, much less data is available in the range of interest to fusion reactor design, particularly in the range 8-13 MeV.

At the P.N. Lebedev Physics Institute early results in the Soviet laser fusion program provided a yield of some 10^4 neutrons from a CD_2 target heated by a focused nanosecond beam at 50 J energy. A larger, nine-beam laser system was developed and delivered 214 J in 6 nsec with an average plasma temperature of 840 eV . Subsequently, a 27 beam spherical geometry system was constructed. At the Sixth European Conference on Controlled Fusion and Plasma Physics at the University of Moscow (August 1973) Soviet workers reported the generation of 600 joules of which 360 joules are transmitted to the target. From measurements of the plasma density in a spherical target pellet it was concluded that central compressions of a factor of thirty at a pressure of 2×10^8 atmospheres were attained. The 600 joule energy of the Soviet laser compares with 840 joules measured at KMS Fusion and up to 1400 joules available at KMS with higher flashing voltage. The Battelle twelve beam laser is claimed to be the world's most powerful, delivering 900 to 1500 joules in 1.5 to 5.0 nanoseconds. Energy breakeven for laser systems is generally believed to lie near a threshold of 10 kilojoules. Such laser systems are presently being planned at the Lawrence Livermore Laboratory and the Lebedev Physics Institute. An economic reactor may require 100 to 1000 kilojoules.

THE U.S. FUSION EFFORT

At present, fusion research within the United States is supported primarily, but not entirely, by the Atomic Energy Commission, within the Division of Controlled Thermonuclear Research (DCTR). The most recent statement of the prospects for fusion power issued by the AEC is contained in a DCTR memorandum of February, 1973, entitled "Fusion Power: An Assessment of Ultimate Potential."[17] We shall refer extensively to this memorandum. At the outset it is stated that

> "Although it is exceedingly difficult to predict when fusion power will become available, it is clear that there are many technical and socio-economic variables which could speed or slow its development. Present estimates indicate that an orderly aggressive program might provide commercial fusion power about the year 2000, so that fusion power could then have a significant impact on electrical power production by the year 2020.
>
> Fusion power has been recognized as having the potential of minimum environmental insult. This expectation is very general and deserves detailed backup. Because some second generation fusion reactor system designs have recently been developed, it is now possible to analyze the ultimate potential of fusion power to a meaningful extent and that is the subject of this report. The approach taken was to evaluate the projected characteristics of fusion power plants in an absolute sense but not to compare fusion systems with current or other projected energy sources."

Thus it is apparent that a systematic comparison of fusion power with its alternatives would comprise a needed addition to the growing literature on energy resources.

In its study the AEC has compared four leading reactor concepts: the tokamak, the theta pinch, the magnetic mirror, and the laser-fusion system. The most developed of the reactor studies, namely the Oak Ridge study[18], was selected tentatively for the Reference Controlled Thermonuclear Reactor, or

Reference CTR. The reference designs will be treated in subsequent sections. Owing to the authoritative nature of the WASH-1239 study we quote the summary conclusions in their entirety:

> "For the purposes of this study the ultimate potential of fusion power has been appraised by considering a set of reference designs for full scale fusion reactors based upon the deuterium-tritium (DT) fuel cycle. One design -- referred to as the Reference Controlled Thermonuclear Reactor or Reference CTR -- was analyzed specifically.
>
> Deuterium for the Reference CTR is obtained directly from sea water at low cost. Tritium is bred in a blanket surrounding the plasma region by neutron absorption in lithium. Typical breeding ratios are about 1.3, giving a doubling time of about a month. With neutron absorbers this ratio can be easily reduced when excess tritium is no longer needed.
>
> During routine power plant operation, tritium is anticipated to be the only radioactive effluent, and it appears to be readily controllable. A tritium leakage rate to the atmosphere from the Reference CTR of 0.0001%/day (based on a system inventory of 6 kG of tritium) appears reasonable from a design standpoint. Assuming that this leakage is to be discharged from the reactor building through a 200 foot stack, the maximum concentration at ground level would be reduced to the point where it would give a maximum dose rate downwind of 1 mrem/yr, i.e., less than 1% of the average dose to the population from natural radioactivity.
>
> The primary source of radioactive waste from a fusion reactor will be the activated structural material of the blanket, which will have a finite useful lifetime within the reactor owing to radiation damage. Approximately 9000 Ci/MW yr. of long-lived radioactivity would be produced in the niobium structure of the Reference CTR. If vanadium were substituted for niobium, this activity would be reduced by a factor of 1000-10,000, depending upon the type and concentration of alloying material.
>
> The DT fuel cycle requires use of a thermal power conversion system. The Reference CTR utilizes a niobium structure which appears capable of operation at 1000°C, which is sufficiently high to provide cycle efficiencies greater than 50%. Using stainless steel for the structure, temperatures are limited to about 500°C, which would give cycle efficiencies near 40%.
>
> Urban siting of fusion power plants would allow rejected heat to be used for heating and cooling and industrial processing. The land despoilment associated with fusion plants appears to be similar to that for fission plants with the exception that urban siting would decrease the land requirements for power transmission.

To start up a fusion power plant, an initial fuel charge of deuterium and tritium will be needed. Thereafter, a continuous supply of deuterium and lithium will be required at the rate of about a kilogram per day. Further tritium shipment will be necessary only to supply the initial charges to start up new power plants. The blanket structure of a fusion plant will become radioactive and will have a finite lifetime of the order of 10-20 years. It will then have to be shipped for reprocessing or storage.

A projected worldwide production of 10^7 MWe from fusion and/or many other types of power will give rise to some resource use conflicts which will have to be resolved. Fusion requirements for niobium for magnets and structure could just be met by known reserves. However, additional reserves may be found or other superconducting magnet materials developed.

To estimate fusion power capital costs, reactor designs developed for the various concepts were analyzed to determine the approximate amounts of the various materials used in their construction. Current prices for the required quantities of these materials in finished form were then used to estimate component costs. These estimates yielded capital costs for the nuclear "island" of roughly the same order as projected for other types of plants in the year 2000. Because of major uncertainties, it is believed that these projections serve only to suggest that fusion power capital costs could be competitive with other energy sources.

Fusion power fuel costs are determined by the costs of deuterium and lithium, and they are essentially negligible -- of the order of 0.007 mils/KWh. The safety and environmental characteristics of fusion reactors should make them potentially acceptable for urban siting, which would further reduce total fusion power costs by savings in transmission costs as well as possible savings associated with the sale of waste heat for building heating and cooling and/or industrial processing.

Fusion reactors appear very attractive when considered from the point of view of accident potential. A runaway reaction will not be possible in a fusion reactor both because of the inherent nature of plasmas and because of the low fuel inventory -- about one gram -- that would be resident in the core during operation.

Studies of the afterheat produced in the Reference CTR indicate that it is possible to evolve a design that is virtually unaffected by a loss-of-coolant accident. An analysis of the consequences of a complete loss of coolant in both the niobium blanket and the shield region of the Reference CTR indicates that all of the afterheat could be removed by thermal radiation and conduction with a temperature rise of no more than about 100°C in the high temperature zone during the first week after the outage, assuming no action whatsoever by automatic controls or the plant operating personnel. If stainless steel were employed for the blanket structure, the afterheat would be reduced by a factor of about two relative to that of niobium, or, if vanadium were employed, the afterheat immediately following shutdown would be reduced by a factor of about four.

The inventory of volatile radioactive material is probably the most important factor to be considered in appraising the requirements for engineered safeguards to protect against accident hazard. For a fusion reactor this means that the tritium inventory, particularly the active inventory in the liquid metal system, is the most vital consideration because it will be the only volatile activity present.

By holding the tritium concentration in the lithium to 1-10 ppm and isolating the lithium and tritium handling equipment in a single, well sealed and monitored compartment, this potential accident hazard can be kept very low.

The national security aspects of fusion power would be many-fold. The U.S. has plentiful deuterium and lithium resources and would therefore be independent of foreign sources. Fusion reactors do not utilize fissionable materials which may be subject to diversion for clandestine purposes. A mature fusion reactor industry would strengthen the country's technological base and foreign sales of fusion reactors would have a favorable effect on the balance of payments. Some reliance on foreign sources of materials such as nickel and chromium will be inherent to fusion as well as many other power sources."

In support of research efforts directed at the achievement of such fusion power reactors by 2000, the AEC currently (FY 1974) spends annually \$44.5 million in the Division of Controlled Thermonuclear Research, of which \$16.3 million is spent on Research and Development, and \$28.2 million on Confinement Systems. This compares to \$350-400 million allocated annually to the LMFBR program. R & D expenditures comprise the development of larger superconducting magnets and larger neutral beam sources for plasma heating Within Confinement Systems, funding for open-systems such as the magnetic mirror is currently \$5.5 million, down slightly from FY 1973. Closed-systems, such as the Princeton Large Torus, the Los Alamos Scyllac, and the Oak Ridge Ormak devices, are currently funded at \$17.7 million, up \$2.8 million from FY 1973. This budget reflects a committment to the construction of the Princeton Large Torus, scheduled for completion by the middle of 1975 at a cost of $13 million. On balance, about 60% of the budget is allocated to low-beta toroidal experiments, 20% to the magnetic mirror, and 20% to the theta pinch systems. In addition, the AEC Division of military applications has a $30 million program in laser fusion for the current fiscal year.

The present plan of attack calls for the leapfrogging of a scientific feasibility experiment, employing inert hydrogen plasma, formerly scheduled for the early 1980's, and proceeding directly to the construction of a device with facilities for burning deuterium-tritium. The target date for hydrogen operation is advanced to 1979-1980. Owing to recent progress in tokamak type experiments, it is presently believed that the deuterium-tritium device would be of similar design, but deuterium-tritium burning magnetic mirrors and theta pinch systems are continuing through the design phase pending the outcome of crucial plasma confinement experiments in these devices over the next few years. Estimated cost of the deuterium-tritium burning experiments is about $100 million per device.

National Laboratory Efforts

The research and development efforts in the national laboratories are concentrated in the AEC experimental facilities at Oak Ridge, Los Alamos, and Livermore, with a smaller program at Argonne National Laboratory. Smaller programs exist at the National Aeronautics and Space Administration Lewis Research Center, the Air Force Special Weapons Center, and the Naval Research Laboratory. Historically the controlled fusion programs evolved from military applications of thermonuclear reactions developed at Los Alamos and Livermore.

Los Alamos Scientific Laboratory

The present efforts at Los Alamos are concenteated in theta-pinch systems (F. Ribe) and laser systems (K. Boyer). In addition to the plasma confinement and plasma compression work associated with the scientific feasibility demonstrations, both groups have conducted preliminary reactor analyses.

The theta-pinch in toroidal geometry (Scyllac) has received the most detailed engineering considerations in collaboration with the Argonne Controlled Fusion Interdisciplinary Group. Following Ribe[19], current construction plans call for a plasma test torus with a 45-60 kilogauss magnetic field scheduled for completion in February 1974. The operating goals include a plasma temperature of approximately 1 keV and a particle density of approximately 2-3 x 10^{16}. Current interest in such theta pinch concepts has stemmed from attainment of plasma parameters in previous linear theta pinch devices which are closer to thermonuclear conditions than other experiments. In particular the linear Scylla theta pinch device, five meters in length, leads to plasma parameters of $T = 2.7$ keV, $N = 2 \times 10^{16}/cm^3$, and t (confinement time) = 11.5×10^{-6}s. Addition of magnetic mirrors increases the confinement time to 18.9×10^{-6}s, thus yielding an Nt product of 10^{11} sec/cm^3, and associated plasma temperature of 2-3 keV. This comprises the best set of plasma parameters obtained in all candidate thermonuclear geometries to date.
The scientific feasibility device which is contemplated would be of 30 meter radius and employ superconducting energy storage for 1 ms cycling of the compression/confinement field. In support of the theta pinch experimental program, Los Alamos supports a plasma diagnostics effort including the use of coupled-cavity interferomtry, field probes with differencing circuits,

and bremsstrahlung luminosity apparatus with on-line Abel inversion for derivation of the plasma beta parameter. The power reactor concept for theta-pinch[20] is summarized in WASH-1239

"A theta-pinch fusion reactor would utilize a shock-heating phase and an adiabatic compression phase. The shock-heating phase would have a risetime of a few hundred nsec and a magnitude of a few tens of kG to drive an implosion of a fully ionized plasma whose density is of the order of $10^{15}cm^{-3}$. After the ion energy associated with the radially directed motion of the plasma implosion has been thermalized, the plasma would assume a temperature characteristic of equilibration of ions and electrons. After a few msec the adiabatic compression field (risetime ~ 10 msec and final value B ≈ 100 to 200 kG) would be applied by energizing a compression coil.

A schematic diagram of a theta pinch reactor system is shown in Figure 5. The inner shock-heating coil with (for example) 8 radial transmission-line feeds is surrounded by a Li-Be-C blanket which has three functions: (a) it absorbs all but a few percent of the 14 MeV neutron energy from the plasma, which its flowing lithium carried out to heat exchangers in the electrical generating plant. (b) It breeds tritium by means of the Li^7 (n, n'α) T and Li^6 (n,α) T reactions. (c) The high Reynolds-number flow of liquid lithium cools the first wall (shock-heating coil).

Outside the inner blanket region is the multiturn compression coil which is energized by the slowly rising current (~ 10 kA per cm of its length) from the secondary of the superconducting magnetic energy store. The compression coil consists of the coiled up parallel-sheet transmission lines which bring in the high voltage to the feed slots of the shock-heating coil. Each side of the horizontal feed of the secondary coil also serves as a ground plane for the high-voltage shock-heating field. Each transmission line delivers of the order of 100 kV to one slot of the shock-heating coil.

Outside the compression coil and its titanium coil backing is the remainder of the neutron blanket for "mopping-up" the last few percent of neutron energy and breeding the last few percent of tritium. Unlike the inner blanket, which would run at ~ 800°C to provide high thermal efficiency of the generating plant, this portion of blanket could run much cooler. Surrounding the outer blanket is a neutron shield, and beyond the shield the radially emerging transmission lines are brought around to make contact with the secondary coil current feeds and the high-voltage shock-heating circuits. To the right is shown the cryogenic energy storage coil in its dewar. At the bottom of the storage coil is the variable-inductance transfer element which reversibly transfers energy from the storage coil to the compression coil and back again.

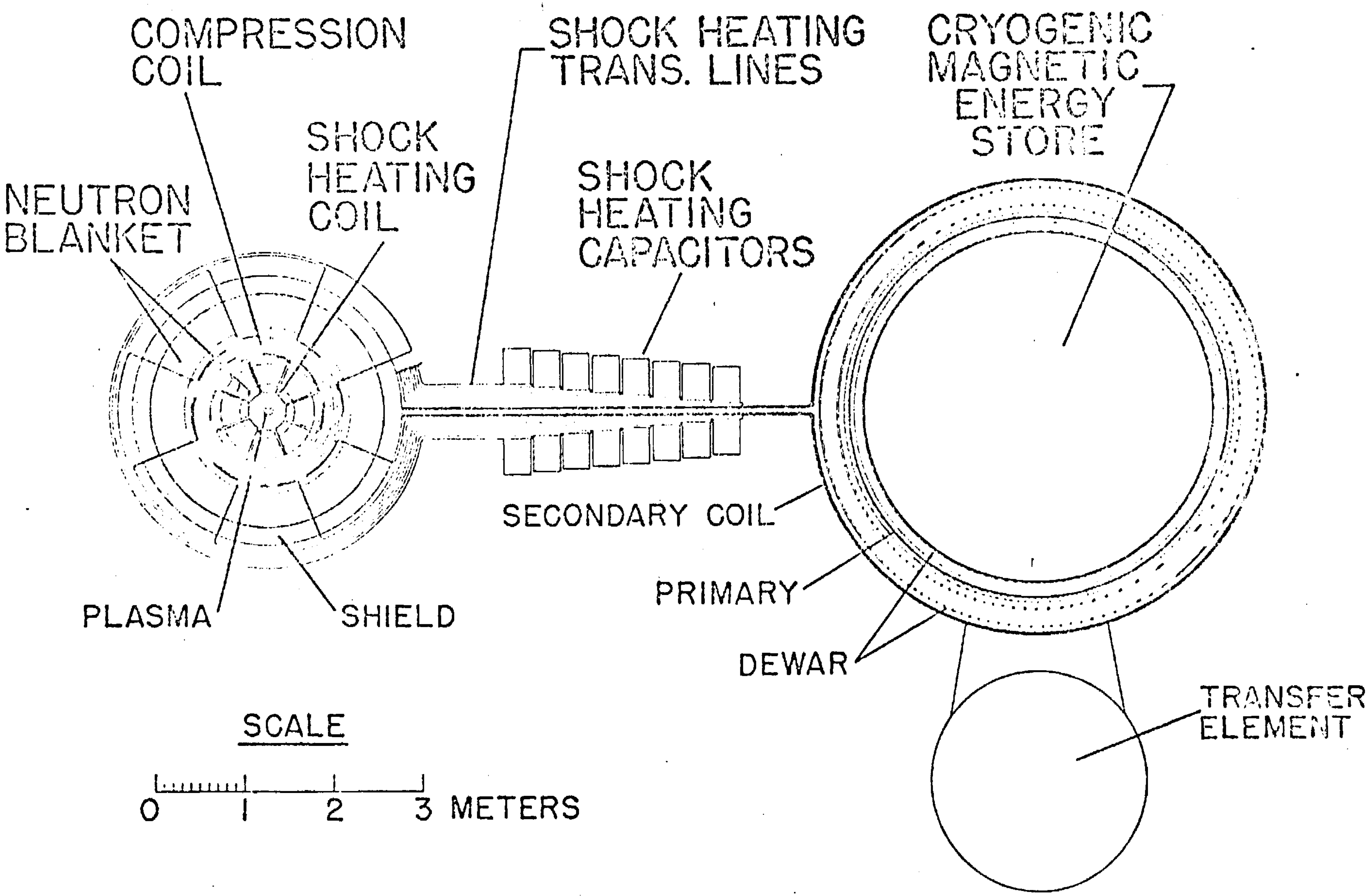

FIGURE 5. Theta Pinch Fusion Reactor (Cross-Section of a Torus). Source: WASH-1239

The laser program at LASL is directed towards the development of 100 joule carbon dioxide gas laser units with amplifiers and multiple path geometry. A multi-kilojoule unit is planned for operation before 1975, and will employ four to six beams. The associated engineering effort has comprised systems studies including blanket mechanical stress and neutronics analyses[21]. The LASL preliminary reactor design is summarized in WASH-1239:

> "A schematic of a wetted-wall Inertial Confinement Thermonuclear Reactor (ICTR) is shown in Figure 6. A DT pellet is injected through a port, which penetrates the blanket, and is initiated at the center of the cavity by a laser pulse; the cavity is defined by the wetted-wall located at a radius of 1.0 m from the center. The subsequent (D+T) burn releases 200 MJ of energy. Within fractions of a microsecond, 50 MJ is deposited within the pellet and 152.5 MJ is generated within the blanket lithium and structural materials.
>
> Within ~ 0.5 ms the pressure pulses generated by the interaction of the pellet with the lithium at the wetted-wall will subside. Within the next few milliseconds, the cavity conditions are equilibrated, ~ 1.6 kg of lithium are vaporized from the protective layer at the wall, and sonic flow conditions of the cavity gases are established at the outlet port.
>
> The flow of hot gases through the cavity outlet port is expanded in a diffuser to supersonic conditions, and the gases are then condensed in a down stream length of duct where a finely atomized spray of liquid lithium is injected. (The spray of atomized droplets is recirculated from the liquid pool at the bottom of the condenser). Downstream of the condenser duct, the mixture of gas and liquid droplets, still at supersonic velocity, is decelerated by turbulent mixing created by a spray of large lithium droplets. (The coarse-droplet spray is provided from a side-stream of the 400°C return flow from the heat exchanger.) The kinetic energy of this mixture is finally absorbed by impacting with a pool of liquid lithium at the bottom of the condenser system.
>
> After ~ 0.2 s, the pressure within the cavity decreases to less than atmospheric, and the blow-down continues during the remaining 0.8 x of the pulse cycle, reducing the cavity pressure to less than 133 N/m^2 (1.0 mm Hg). The cycle is then repeated with the initiation of another pellet.
>
> The energy deposited within the blanket is removed by circulating the lithium through an external heat exchanger. Lithium, flowing at 400°C from the heat exchanger, is returned to a plenum between the 1.0 cm-thick wetted-wall and the 5.0 cm-thick inner structural wall, which serves to restrain the movement of the inner blanket boundary caused by the pressure waves generated within the blanket

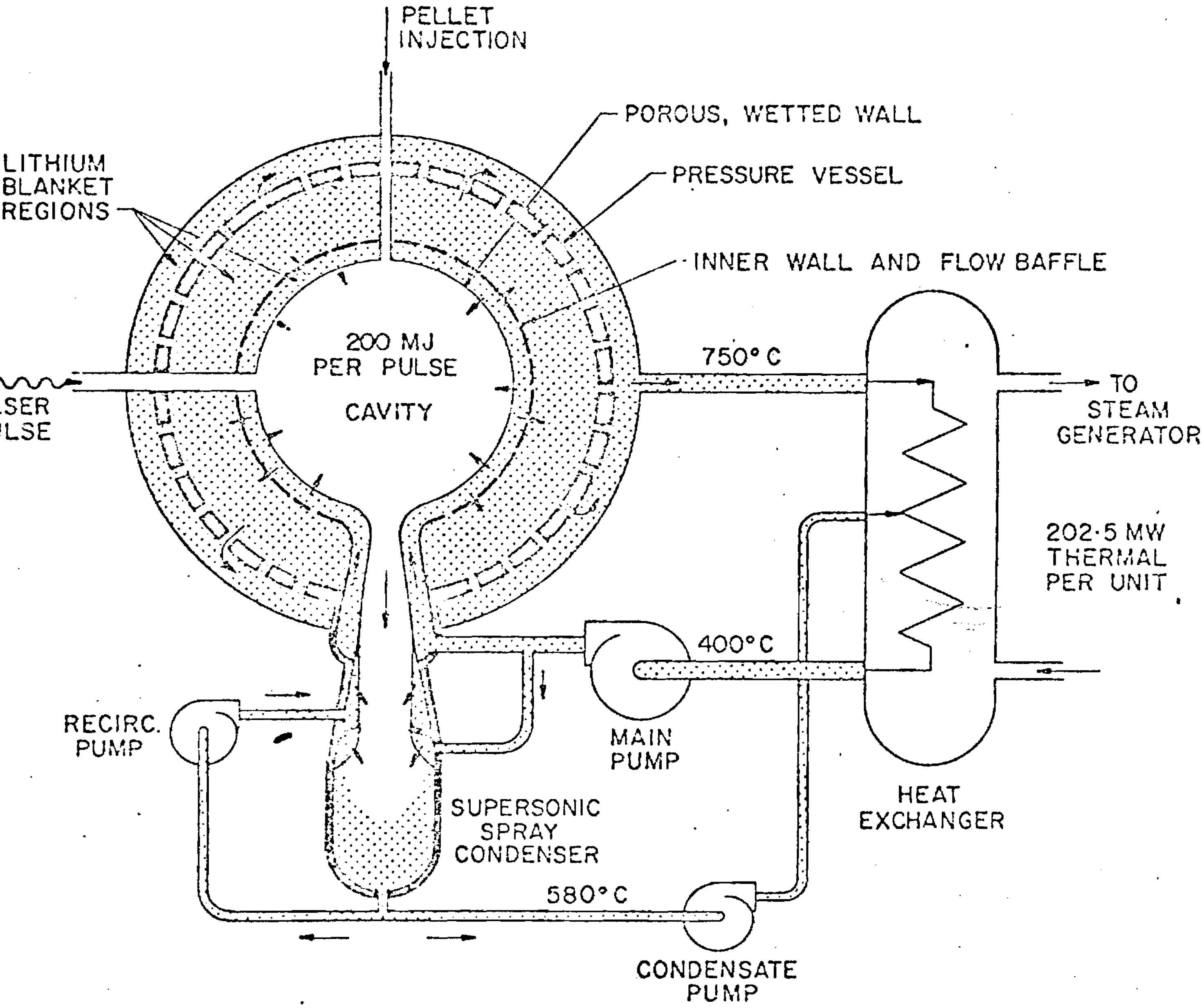

FIGURE 6. LASL Laser-Driven Fusion Reactor. Source: WASH-1239

and the cavity pressure. Located a few centimeters behind the wetted-wall, the inner structural wall also serves as a flow baffle for distributing the radial outflow. The wetted-wall moves along with the structural wall through hydrodynamic coupling, and, if needed, through mechanical attachments.

The minimum power level is based on a thermal output of ~ 200 MW, from one ICTR. Higher power levels may be obtained by combining several ICTRs in a reactor system, thereby increasing both the versatility and the overall ratio of actual operating power to full design power. The nominal thermal power level for a conceptual plant was arbitrarily chosen to be ~ 2000 MW, requiring ten modular ICTRs.

Lawrence Livermore Laboratory

Early work in compression of thermonuclear fuels to ignition temperatures for military applications prompted both magnetically confined and, later, inertially confined controlled fusion investigations at LLL as well as LASL. The program in magnetic confinement has included the Christofilos E-layer or Astron concept and the magnetic mirror concept investigated by Post and Coensgen, under the overall direction of T. K. Fowler. While now discontinued, some of the earliest reactor system designs evolved from the Astron group. At present, emphasis in magnetic confinement is on plasma tests with the 2XII mirror device. An associated reactor system study effort is in progress. The laser-induced inertial confinement technique is being developed under J. Nuckolls and includes advanced computer calculations as well as reactor system studies complementary to the LASL effort.

The magnetic confinement program has been described by Coensgen[22]. The outstanding characteristics of the mirror concept include the highest attained plasma temperatures to date - 10 keV is approached in some experiments. Plasma density is low - approximately 6 x $10^{13}/cm^3$ in 2XII experiments using a titanium evaporator. Current emphasis is directed towards the enhancement of confinement time and the demonstration of efficient, neutral beam heating techniques. Confinement times have been extended to approximately 2.2 milliseconds using minimum-B confinement techniques developed from the Ioffe hexapole geometry. Present neutral beam heating work is directed toward beam currents of order 10 amperes, with progression to 100 amperes projected. The basis for use of neutral beams in these mirror experiments is the positive potential developed within the plasma as electrons preferentially leak out the ends of the magnetic mirrors.

Fusion power reactor studies have been undertaken at LLL and incorporate both D-T and D-He^3 fuel cycles. The magnetic field in the D-T systems are of the order 42 kg in the plasma, and for D-He^3 systems 70 kg. The D-T reactor is described in WASH-1239:

> "Designed to produce 500 MW(e), the LLL DT mirror reactor design may be considered as having three main parts: a magnetically contained plasma volume in which the fusion reactions take place, an ion injection and plasma heating system requiring electrical power input, and a combination thermal and direct energy converter system. The thermal portion of the converter system converts the neutron kinetic energy to thermal energy in a blanket surrounding the plasma confinement zone. The blanket breeds tritium for fuel replenishment. The second element of the energy converter system is the direct converter which accepts energetic charged particles which escape from the plasma confinement zone and it converts their energy to high voltage dc power. A fraction of this direct converter power is then fed back to the ion injection system to sustain the reaction and maintain the plasma. The reactor may be generally classified as a relatively low gain energy amplifier. This concept of combining thermal and direct conversion should be applicable to any fusion containment system; however, it is especially attractive for mirror systems because it furnishes a means to minimize the adverse effects of end losses. The direct conversion subsystem operates in a sequence of four steps: (1) expansion, (2) charge separation, (3) deceleration and collection, (4) conversion to a common potential. The first three steps of this process are as follows. The reaction products escape from the mirrors at a low ion density ($10^8 cm^{-3}$) which is further decreased to $10^6 cm^{-3}$ by expansion into a large, flat, fan shaped chamber. Expansion is accomplished by coupling an external radial magnetic field to the

mirror field and allowing the field to decrease from its high level at the mirrors (approximately 150 kilogauss) to levels of about 500 gauss. The expansion also converts particle rotational energy to translational energy in inverse proportion to the field change. At the end of this expander field, electrons are separated from the ions by abruptly diverting the field lines. The electrons behave adiabatically and remain on the field lines while the ions cross the field lines and enter the collector region.

The ions emerge from the expander with a considerable spread in energy. To recover this energy at high efficiency the ions are passed through a series of electrostatically focusing collectors within which they are progressively decelerated. The ions are decelerated to a low residual energy and then diverted into a collector. Experiments at LLL have demonstrated overall collection efficiencies in excess of 80% and further improvements are expected.

The final step of direct conversion is the transformation of the electrical energy to a common potential. This is accomplished by an inverter-rectifier system using commercially available equipment.

The approximate plasma conditions are as follows: average ion energy = 400 keV, average electron energy = 40 keV, total power output = 1330 Mw, plasma beta = 0.9, plasma density = 10^{14}cm^{-3}, and plasma radius = 4.3 meters. A schematic of the system is shown in Figure 7.

Systems studies of the magnetic mirror concept center about the use of electrostatic conversion of the kinetic energy of the charged reaction products generated in He^3-enriched fuel cycles. Sophisticated calculations of end loss phenomena have suggested that such He^3-enriched systems may have marginal Q - that is, the ratio of power out to power in - and excessive circulating power. Thus systems studies include D-T fuel cycles which offer potentially higher Q, though most of the electrostatic direct conversion is traded for the inefficiencies of a thermal engine. In view of the potential attractiveness of the He^3-enriched fuel cycles, from an environmental standpoint, ongoing research in electrostatic converters is in progress as well as efforts to reduce end losses and achieve a higher system Q. The latter effort requires a better understanding of the nature of microinstabilities within thermonuclear plasmas. Such an understanding has been greatly assisted

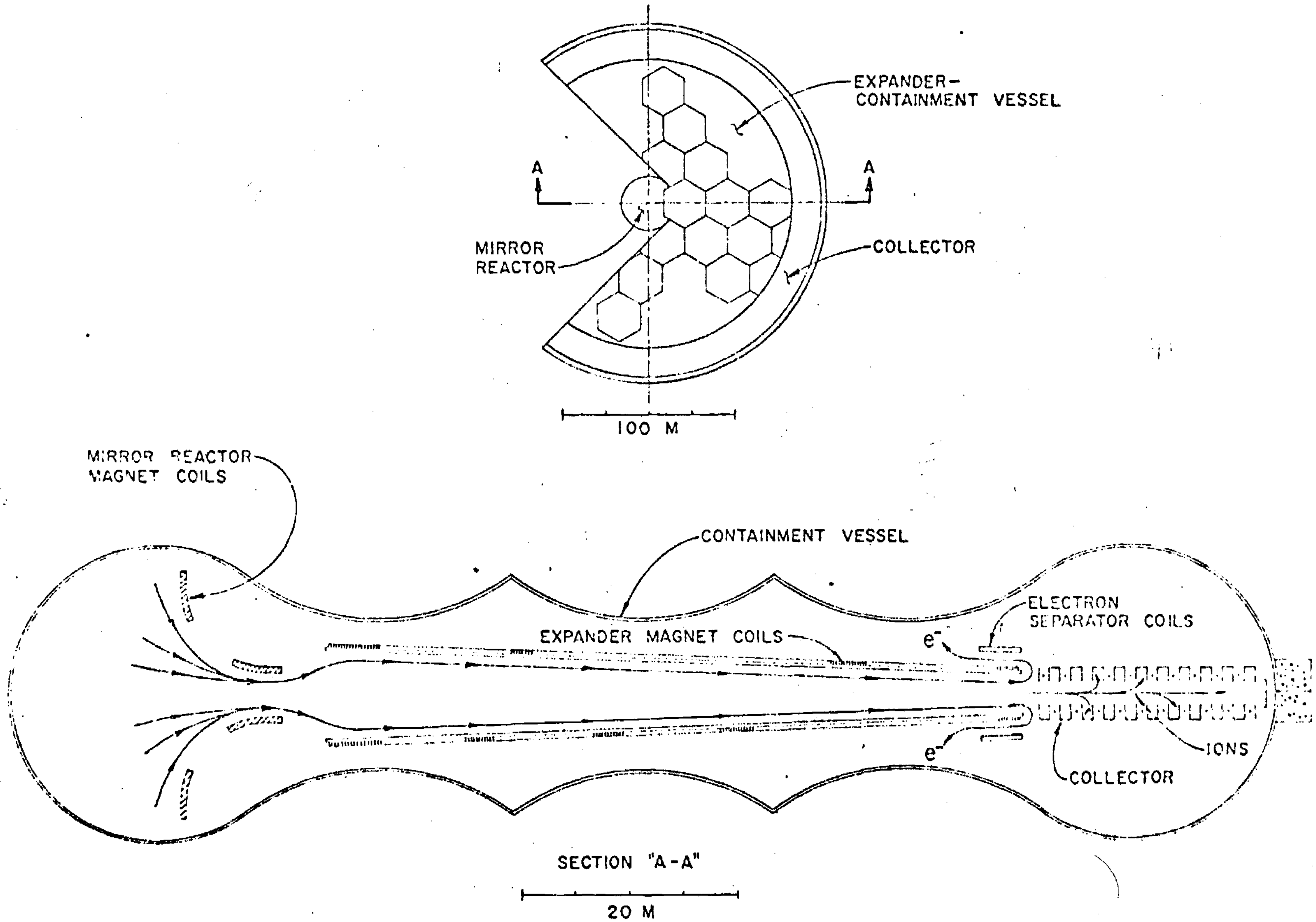

FIGURE 7. LLL Mirror Reactor With Direct Converter. Source: WASH-1239

by an ongoing program of computer simulation of such instabilities.

The LLL laser-fusion effort is described recently by Nuckolls.[23,24] Key elements of the program include computer calculations of implosion phenomena, laser technology, and reactor studies. The computer program incorporates several physical phenomena including hydrodynamics, optical absorption, coulomb coupling of charged-particles species, suprathermal electron spectra, thermal diffusion, magnetic field and MHD effects, photonics, nuclear reaction kinetics, and materials properties under extreme conditions of temperature and pressure. The laser technology effort at LLL includes a design study and funding request for construction of a 10 kilojoule neodymium glass laser system for subnanosecond spherical irradiation of pellets. It is expected that with such a system fusion power output equal to laser power input can be demonstrated. In addition to the neodymium-glass laser investigations, LLL is investigating the short-wavelength (1722 Å) xenon laser which offers the promise of better energy deposition and higher efficiency (25%) than either CO_2 or neodymium-glass lasers can obtain. In addition to the physics calculations and laser technology activity LLL works with LASL in the development of laser-driven fusion reactor concepts, which are presently in an earlier stage of evolution than the magnetically-confined fusion reactor system studies.

Oak Ridge National Laboratory

In addition to the early DCX experiment and fusion technology investigations ORNL carries out magnetic confinement investigations on both magnetic mirror and tokamak configurations. Advanced design of prototype fusion power plants in laser and tokamak form are being conducted, and the latter are amongst the most detailed studies to date on complete systems.

The principal magnetic confinement devices employed in ORNL experiments are the Ormak (Oak Ridge Tokamak) and the Elmo toroidal mirror. Recent results obtained on the Ormak device have been described by J. Clarke of the ORNL Thermonuclear Division[25]. Topics presently under study include neutral beam injection and heating, the classical slowing down process, injection effects on plasma stability, and plasma relaxation mechanisms. Present plasma behavior exhibited by Ormak as well as the Soviet T-3 and Princeton ST devices confirms the principle of scaling according to the pseudo-classical diffusion theory, and Ormak is found to have the lowest collisionality of any existing machine in its class. Neutral beam injection has been tested and has demonstrated 20% heating increments over the ohmic limit. Four neutral beam injection units are to be installed with 120 kW beam power capability per unit in the present program. Immediate goal is to obtain 1 keV plasma temperatures.

Associated with the Oak Ridge tokamak plasma experiments are design studies of a prototype commercial fusion power plant. The current design study[18] has formed the basis of the reference reactor for the WASH-1239 report. The summary description follows:

> "The principal featrues of the conceptual design of a full scale tokamak chosen as the Reference CTR are shown in Figure 8. The torus structure is divided into six sectors to facilitate construction and maintenance. Four of these are shown assembled and positioned around the poloidal magnet core. In the left foreground a fifth is assembled and ready to be moved into position. In the right foreground partially assembled magnet coils for the sixth are illustrated. Note the massive steel reinforcing rings that contain the superconducting coils in their inner flanges. Figure 9 is a schematic of the approximately one meter thick blanket region which surrounds the toroidal plasma. It consists of a set of 60 segments, each of which consists of a 2.5 mm thick niobium shell. ...These segments contain a long, slender, central "island" of graphite surrounded by a lithium-filled duct. Lithium coolant would be circulated at about 30 cm/sec around this closed loop by an electromagnetic pump at one end. Tritium is bred by neutron absorption in the lithium. A typical breeding

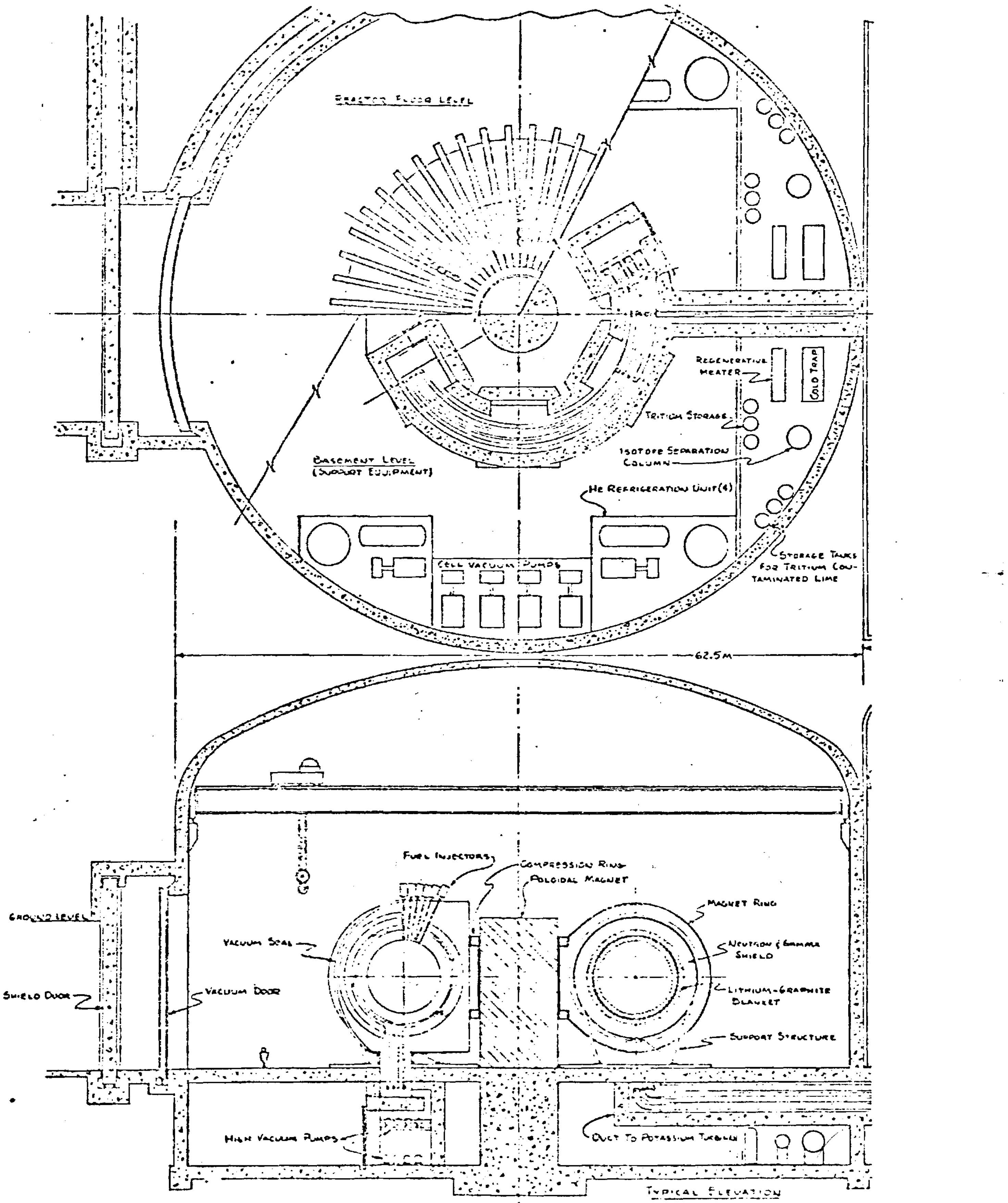

FIGURE 8. Reference CTR: ORNL Concept. Source: WASH-1239

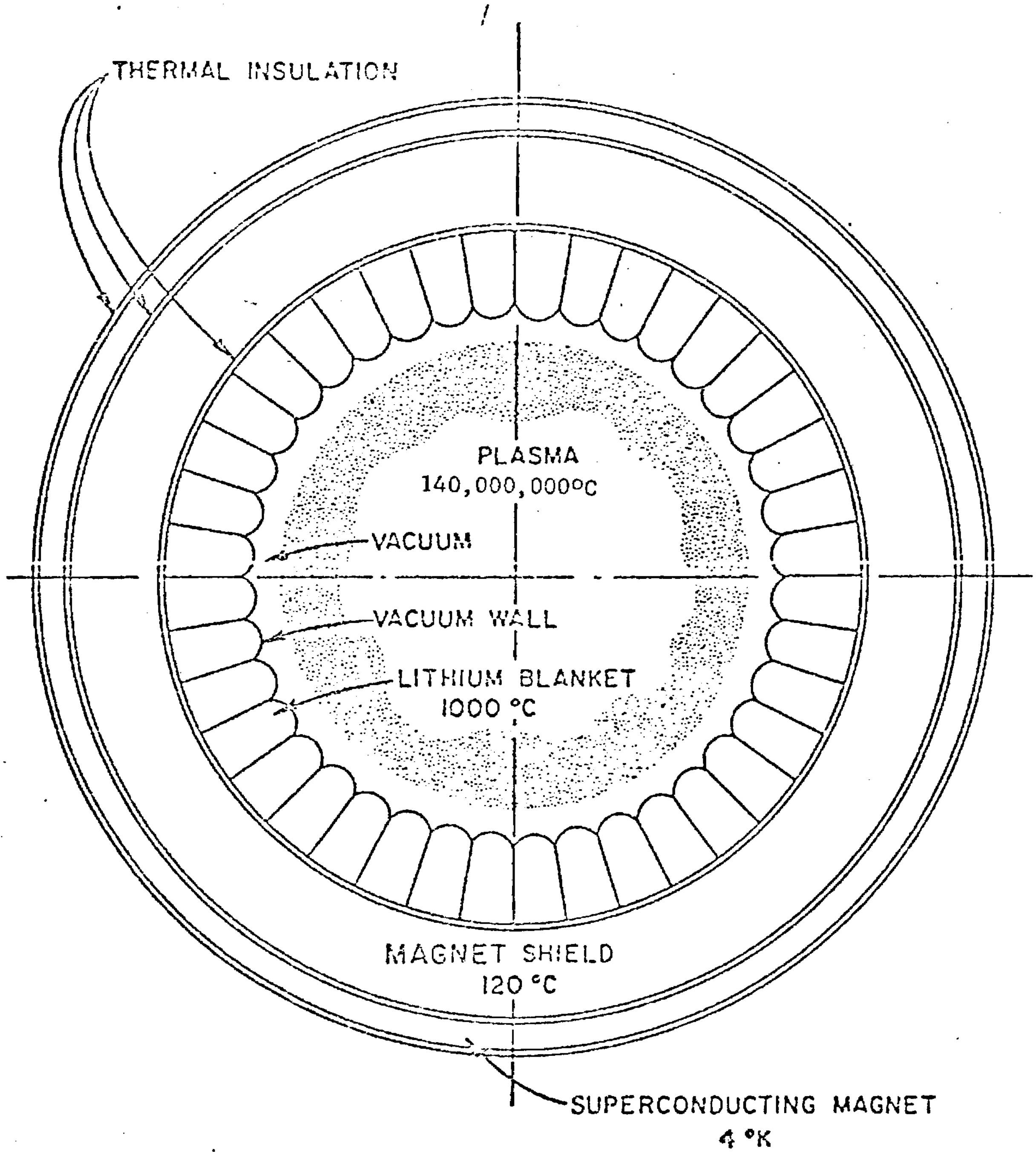

FIGURE 9. Section Through Toroidal Core of ORNL Design. Source: WASH-1239

ratio is 1.3, giving a doubling time of about a month. (Addition of neutron absorbers can easily reduce this ratio when excess tritium is no longer needed). A set of tubes installed in the lithium blanket utilized the heat generated in the blanket to boil potassium. One set of the ring-shaped manifolds would carry the liquid potassium feed to the blanket from pipes in a duct beneath the reactor floor, and the other set carries potassium vapor to vapor pipes that extend around under the reactor and out to a potassium vapor turbine in the adjacent turbine hall (see Figure 10).

A magnet shield about 1 m thick attenuates radiation leaking from the blanket region into the liquid helium-cooled superconducting magnets so that the radiation energy deposited in them would be about 1 kW(t), and hence the power required for the liquid helium refrigeration system can be held to about 2 MW(e).

Six neutral beam injectors for plasma heating and refueling are mounted near the top of each sextant so that fuel injection takes place through the parting planes between sextants.

Magnetic mirror developments pursued at ORNL have evolved to the so-called bumpy torus (Elmo) concept, in which the end losses inherent to mirror confinement devices are circumvented by arranging a series of mirror cells in a circular geometry. In the current year construction of such a device has been partially completed. Basic plasma studies relevant to the mirror apprach have been conducted in the related IMP device.

Reactor studies for laser-driven fusion have been conducted at ORNL and incorporate the rotating lithium vortex concept of A. Fraas[26]. A summary description of the BLASCON system is contained in the WASH-1239 report and is excerpted as follows:

"If lasers can be economically utilized to ignite DT pellets to give small thermonuclear explosions, it may be possible to build reactors for central stations, ships, and spacecraft propulsion. Analyses and model tests indicate that, by igniting the pellets in the cavity of a vortex formed in a pool of liquid lithium, the explosion can be contained in conventional pressure vessels at a vessel capital cost of only about $10/kw(e). The neutron economy would be excellent -- the breeding ratio could be 1.3 to 1.5. If applied to reactors for central stations or ships, the concept would permit the construction of economic, thermonuclear reactors

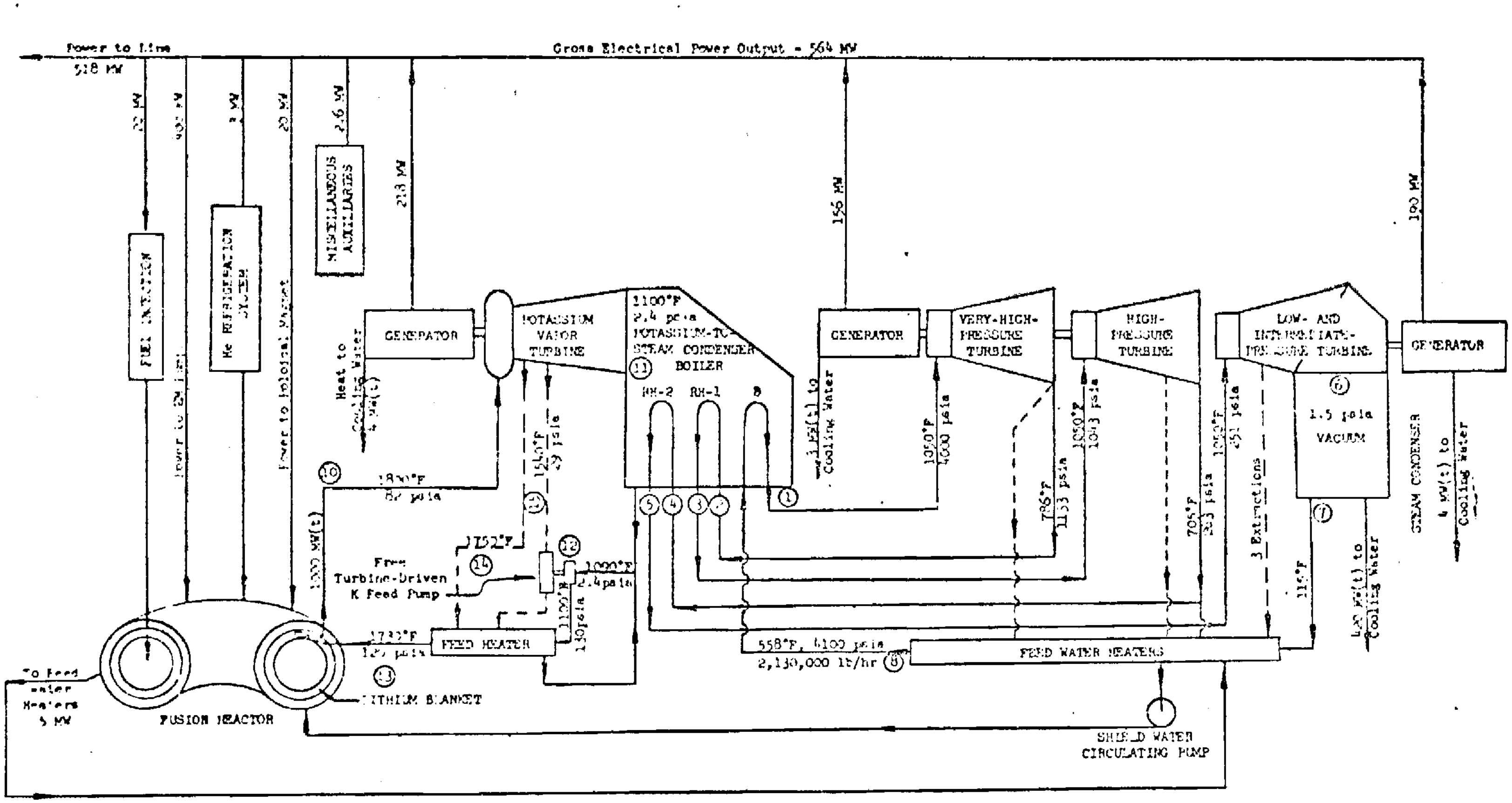

FIGURE 10. Potassium-steam Binary-Vapor Cycle Energy Conversion System For ORNL Fusion Reactor. Source: WASH-1239

in sizes possibly as small as 100 MW(t). There would be no need for large cryogenic magnets, and no problem with fast neutron damage or neutron activation of structure. If applied to spacecraft propulsion the laser-exploded pellets might give a system whose propellant requirement for a typical Earth-Mars-Earth mission would be only about 10% those of a Rover-type nuclear rocket.

Frozen DT particles could be ignited at intervals of 10 to 20 sec and the energy of the explosions absorbed in a rapidly swirling pool of molten lithium contained in a massive pressure vessel perhaps 10 or 15 ft. in diameter having a configuration similar to that of Figure 11. With a sufficiently high swirl velocity, a free vortex would form at the center of the swirling pool to provide a cavity into which a deuterium-tritium pellet could be fired. When the pellet approached the bottom of the cavity in the vortex, a laser beam could be triggered to ignite the pellet, and the energy released in the subsequent fusion reaction could be absorbed in the molten lithium. Drawing off the lithium from the bottom of the pressure vessel would help stabilize the vortex. The lithium would be circulated to heat exchangers that could serve either to boil the working fluid for a Rankine cycle or heat the gas of a Brayton cycle. Other thermodynamic cycles could of course be employed, but the Rankine and Brayton cycles appear to be the most attractive. The lithium would be returned through pumps to tangential nozzles in the perimeter of the pressure vessel to maintain the desired vortex so that particles would be injected to a point close to the center of mass of the lithium. The operating temperature of the lithium would depend in part on the choice of containment system material, e.g., about 900°F if a chrome- moly steel were used and perhaps 1800°F if niobium were employed.

Key to the success of the BLASCON concept has involved current experiments with bubble injection for attenuation of the hydrodynamic shock wave resulting from pellet ignition. Experiments with a lucite model employing water have demonstrated an eightfold reduction of shock intensity by means of bubble injection and using a capacitor discharge for simulation of the pellet impulse. As a result it is expected that reduction in wall thickness of the reaction chamber outer wall from 80 cm to 10 cm may be possible for minimum-burn pellets in actual reactors.

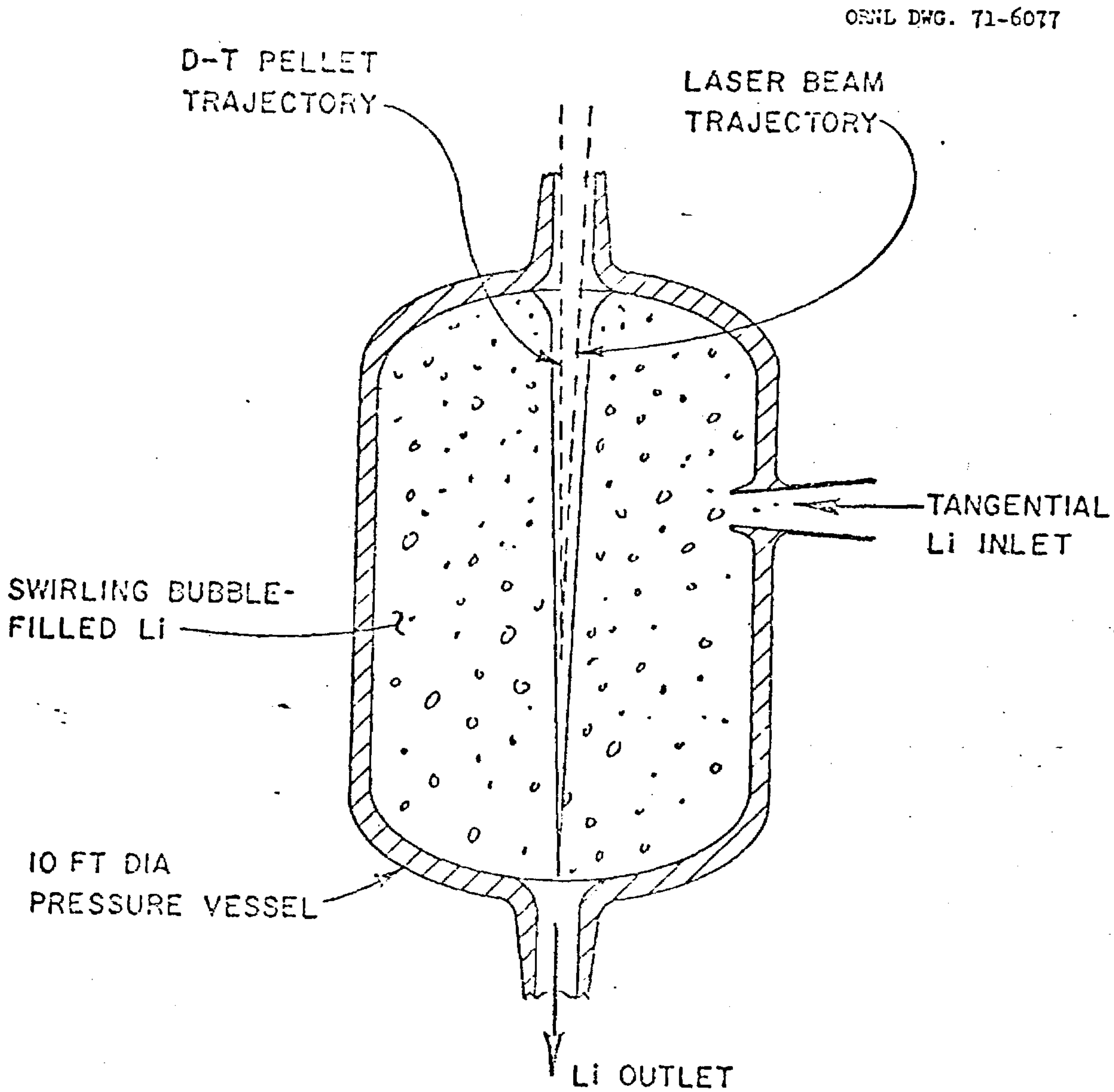

FIGURE 11. ORNL Laser-Driven Fusion Reactor Concept. Rotating Lithium Vortex. Source: WASH-1239

Argonne National Laboratory

An interdisciplinary working group in controlled fusion at Argonne National Laboratory is collaborating with LASL in the detailed investigation of prototype theta pinch power reactor concepts. Materials research in support of fusion technology underway at ANL includes superconducting magnet research, insulator research, and ionic impact studies. In addition, ANL is investigating magnetohydrodyanmic conversion of fusion energy.

Lewis Research Center

The fundamental problem of rocket propulsion has historically been an energy problem, and amongst the concepts investigated at NASA Lewis Research Center since the 1958 Geneva Conference has been the feasibility of thermonuclear rocket propulsion. A comparison of the technological problems involved in fusion space propulsion and fusion power generation has been performed by J. R. Roth, W. D. Rayle, and J. J. Reinmann[27]. Mission analyses indicate the potential of fusion propulsion for both interplanetary[28] and possible interstellar[29] missions.

Analytical work on the D-He^3 fuel cycle performed at NASA Lewis Research Center has contributed to our understanding of this environmentally promising fuel system[30]. Studies of energy transfer in thermonuclear plasmas[31] bear on the feasibility of magnetohydrodynamic conversion of fusion power for electric power generation. Experimental work on plasmas and superconducting magnet systems has accelerated the state-of-the-art in fusion confinement systems.[32] Present investigations at Lewis center about the toroidal mirror concept, shown in Figure 12. Exhaust thrust would be obtained by means of a plasma

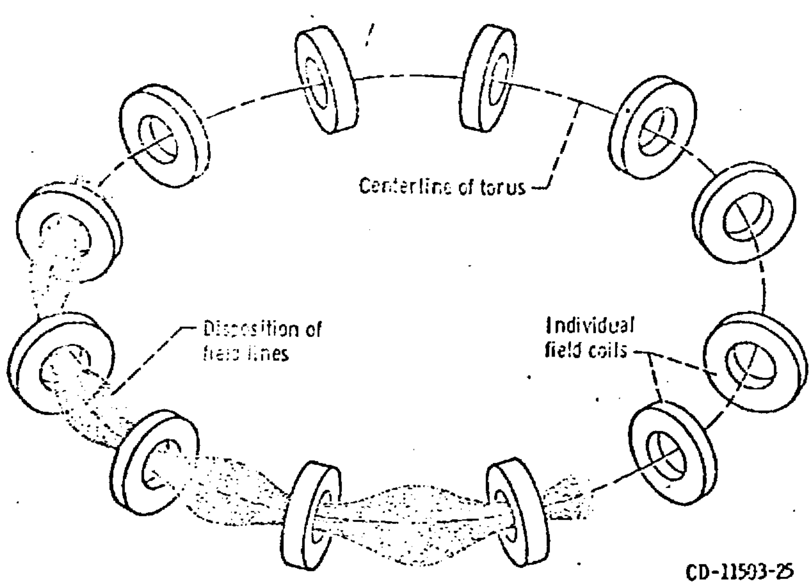

FIGURE 12. Bumpy-torus Confinement Concept. Source: NASA TN D-7353

divertor similar to that contemplated for ash and impurity cleanup in a power producing reactor. The concept is shown in Figure 13. Remarking on the lower duty-cycle and the economics of space propulsion, Teller[33] has remarked that space propulsion applications of nuclear fusion might actually precede terrestrial power applications.

Non-Profit Research Institute Efforts

Activities of the non-profit research institutes encompass a variety of tasks related to the development of controlled nuclear fusion, from plasma physics work to technology development to systems studies. Thus experimental laser development at Battelle Memorial Institute has progressed to the point where fusion feasibility experiments have been planned. The present Battelle laser system, a Hadron neodymium-glass seven-stage device, incorporates a large multihead amplifier and beam splitting system. At 900 to 1500 joules the system is reported to be the world's most powerful laser. Full potential of the twelve-beam system is said to be 2500 to 3000 joules and is to be available in coming months. At this level it is expected that the conversion of 5 to 10 percent of the laser energy to fusion energy can be demonstrated in two years. The Battelle work includes development of theoretical models and computer codes.[34]

In an assessment of Calfornia power needs Stanford Research Institute[35] has provided an independent evaluation of the prospects for fusion power. Highlights of this evaluation are extracted below:

> "The SRI study team believes that 20 to 50 years of development work will be required before fusion reactors are freely accepted by utilities in the United States. This conclusion is based partly on the hsitory of fission reactor development and partly on the timetable suggest by analogous events in the fusion development as tabulated below (see Figure 14).

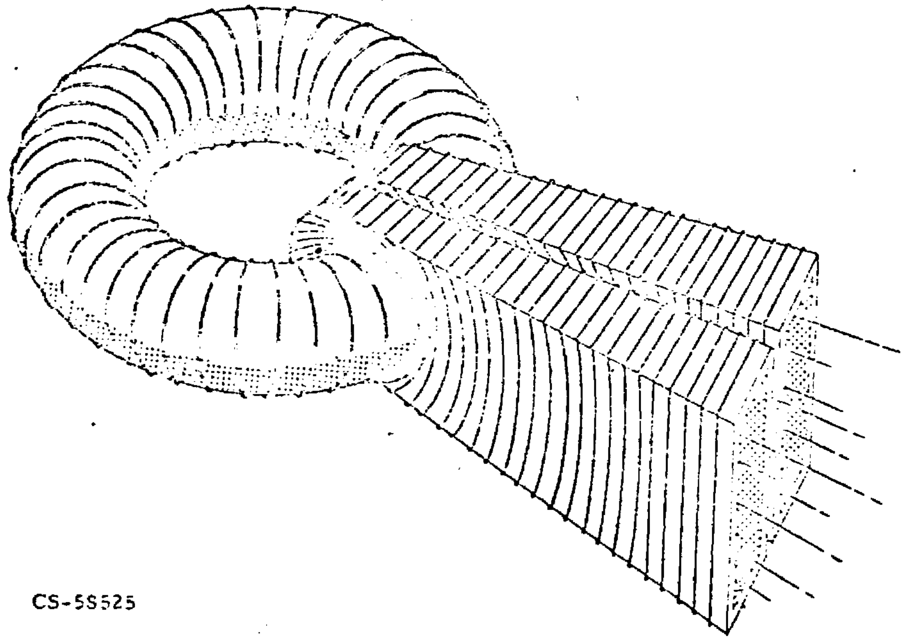

FIGURE 13. Application of Plasma Divertor to Space Propulsion.
Source: NASA TM X-67826

FIGURE 14. Comparative Historical Development of Fission and Fusion Power

	FISSION		FUSION	
Action	Year	Participant	Year	Participant
Observed	1934	Fermi, accelerator particle bombardment	1920	Eddington, solar reactions
Identified	1939		1929-39	Other Sources
Sustained Reaction	1942	CP-1	1976-80 or 1976-85	--
Power Extracted	1952	--	1985-90	
Utility Acceptance	1953	Central Electric Generating Board	2000-30	
	1960-67	Southern California Edison		
	1963-69	Jersey Central Power and Light		

Source: SRI (Ref. 35)

> It also appears that the materials problems arising from the intense, high energy neutron flux and the difficulties caused by the extremely high temperature plasma reactions in a confined space will require lengthy and expensive research and testing. The economic size of these plants is expected to be substantially larger than that of current fission reactors. Sizes of 3000 to 10,000 MW are mentioned as minimum economic ones. The utility grid or regional demand must be large before plants of such size can be accomodated. Locations which guarantee adequate cooling (7,500 to 25,000 MW of heat must be rejected) will also pose some problem...
>
> The first generation of fusion reactors will be limited in ultimate capacity by the availability of lithium. The world lithium supply, if used in this way, is estimated as the equivalent in energy content to all fossil fuels. The availability of lithium, as with many other materials, depends on the assumed worth. Higher values would undoubtedly result in discovery of more lithium...
>
> Advanced fusion reactors may extract electric power directly from the flowing plasma as a magnetohydrodynamic generator does. Such a system could have efficiencies as great as 80%, thus reducing the heat rejection requirements by factors of 3 to 6, and reducing fuel requirements by a factor of 2 or more.

This estimate of fusion availability by SRI is consistent with AEC goals and includes the period from demonstration plant operation to utility acceptance c. 2000-2030. It is consistent with the AEC estimate in WASH-1239 that "fusion could then have a significant impact on electrical power production by the year 2020." The estimate of thermal output must be tempered with the understanding that laser or electron beam driven fusion may permit power plants of as little as 100 MW thermal output.

The newly formed Electric Power Research Institute is expected to provide a utility-sponsored perspective on the question of controlled fusion. In this perspective it is reasonable to expect further consideration of economic factors governing the introduction of fusion power.

Private Efforts

The principal private efforts in nuclear fusion are those at General

Atomic Company and KMS Fusion. In addition Exxon Nuclear Company has recently begun investigations under Harold Forsen.

General Atomic is presently conducting experiments with two major plasma confinement devices, the dc Octopole and Doublet II. Planning for another major confinement experiment, Doublet III, is in progress. Fusion technology studies are presently being expanded. The basic theme of present experiments at General Atomic is the exploration of tokamaks with a noncircular cross-section. Insight into the noncircular cross-section is due to T. Ohkawa of General Atomic. Recently, T. Jensen of General Atomic has described the basis of noncircular cross-section experiments.[36] Plasma theory for tokamak devices shows that a high value of the parameter q is desirable, where $q = B_t r/B_p R$. Here B_t and B_p are the toroidal and poloidal components of the magnetic field, r and R are the minor and major radii of the torus, respectively. Thus it is desirable to have a minor radius as large as possible, as suggested by the comparatively "thick" cross-sections of the circular tokamak designs. But there are engineering limits to such a trend, i.e. space requirements for the neutron shielding, magnet coils, blanket, and structural support. Accordingly, it is proposed to increase the effective minor radius of the tokamak by using an elliptiform cross-section.

It was remarked earlier that the Battelle laser has operated at up to 1500 joules. At KMS Fusion an 80 mm driver laser is used with an output energy of 250-350 joules. Using a G.E. laser amplifier system, input at 200 joules (3 ns pulsewidth), KMS have obtained a measured output from the first six modules of about 840 joules at 8 kV flashing voltage. This is said to compare to a best Soviet value of 600 joules. KMS claim to have delivered on target 550 joules, compared to the Soviet figure 360 joules.

The predicted output of the KMS laser using seven modules flashed at 8 kV is about 990 joules, and at 9 kV is about 1400 joules - comparable to the Battelle number.[37]

In target experiments begun in October 1973, KMS had illuminated deuterated polyethylene spheres about 0.1 mm in diameter and had produced about 0.5×10^6 neutrons per pulse. The D-D neutrons, identified by their characteristic velocity, are believed to have originated in collective and not thermal processes. A significant observation at KMS is that light reflection by the plasma is considerably less than originally predicted.[38]

For years Physics International Company has supplied the defense community with large, pulsed electron beam machines, and it was proposed as early as 1965 to employ such beams to drive fusion reactions. Experimental programs are presently under way at the Naval Research Laboratories, Sandia Laboratories, Cornell University, Lawrence Livermore Laboratory, Air Force Special Weapons Laboratory, North Carolina State University and laboratories in the Soviet Union.

Using 11 kilojoules investigators at LLL have measured 1.7×10^{10} neutrons per pulse from deuterated targets. As in laser experiments the neutrons do not arise entirely from thermal processes but are in part due to ions accelerated in the electric field. Typically, electron beam machines store up to 200 kilojoules which is delivered in 30-80 nanoseconds. The largest available machine, "Aurora", built by Physics International and operated by Harry Diamond Laboratories in White Oak, Maryland can deliver 2.5-3.0 megajoules in 125 nanoseconds.

Thus, while electron beam devices appear to develop greater total energy than presently available lasers, the pulse width is excessive on the nanosecond scale of pellet implosion which is required by calculations.

Efforts are presently under way at Maxwell Laboratories in San Diego to develop equipment with a shorter pulse.[39]

University Efforts

In addition to the large program at Princeton Plasma Physics Laboratory (PPPL), active programs are being pursued at M.I.T., University of Texas, Cornell, Rutgers, University of Wisconsin, University of Illinois, and the University of Rochester. In total some thirty colleges and universities are involved.

The role of university programs has been recently described by B. Miller.[40] Outside of the large hardware program at PPPL, most of the university effort is subsumed within the Research branch of the Division of Controlled Thermonuclear Research. Of the approximately $7 million in the Research budget, about $4.2 million is allocated to the AEC laboratories and about $2.8 million to the thirty university or "off-site" locations. General categories of research are: 1) plasma properties, 2) plasma physics, 3) plasma diagnostics, 4) computer techniques, 5) exploratory concepts, and 6) atomic physics. Reversing the trend of previous years the budget allocated to these programs is expected to increase in the current year, both in theoretical and experimental areas. Plasma diagnostics and computer techniques, particularly, are expected to increase rapidly. In general, university efforts will be directed towards progress in confinement goals and on new departures, with primary emphasis on the former.

The large effort at Princeton Plasma Physics Laboratory, which operates largely on an AEC contractor basis, has culminated in the proposal to construct PLT (Princeton Large Torus). This device, basically a tokamak with added flexibility in the form of specially shaped and programmed transverse fields, is in the beginning of the construction phase and is scheduled for completion in mid-1975, at a cost of $13 million. At about the same time the Soviet Union is expected to complete T-10, roughly the same size as PLT. The PLT has a plasma minor radius of 45 cm, coil bore of 90 cm, and a major radius of 140 cm. Plasma current will be about 1.6 megamperes, which compares to the current record of 230 kiloamperes obtained in the Soviet T-4 and French TFR. Plasma temperatures of 2-3 keV are expected with a confinement time of about 0.3 second. Magnetic field will be about 50 kilogauss on-axis.

As an extension of the PPPL toroidal confinement program, a prototype fusion power reactor design has been developed. The design is superficially similar to the ORNL concept (Figure 8) but incorporates a plasma divertor, uses stainless steel instead of niobium in the first wall, uses flibe (2 LiF. BeF_2) instead of elemental lithium, and employs helium gas instead of potassium vapor to cool the blanket. The design is further detailed in WASH-1239:

The guiding principles on which this design was based were as follows:

1. The maximum magnetic field at the superconductor of the toroidal field coils was to be limited to 160 kilogauss. This field strength is somewhat higher than the present state-of-the-art level.
2. A divertor was to be included since the reactor was expected to operate essentially on a steady state basis.
3. Inexpensive, readily available materials and common techniques were to be utilized as much as possible.
4. The "safety factor", q, was chosen to be 2.0, a reasonable expected improvement over present experimental accomplishments.
5. The aspect ratio, A, was expected to exceed 3.0; the plasma ion density to approximate $10^{14}cm^{-3}$; the plasma temperature to be about 15 kev. The plasma composition was assumed to be equal parts of D and T. The reactor's electrical output was expected to be about 2000 MW(e) and a thermal cycle efficiency of 40% was assumed.

The resulting design (Figure 15) in part reflects the difficulty in placing a divertor on a tokamak reactor. The divertor windings

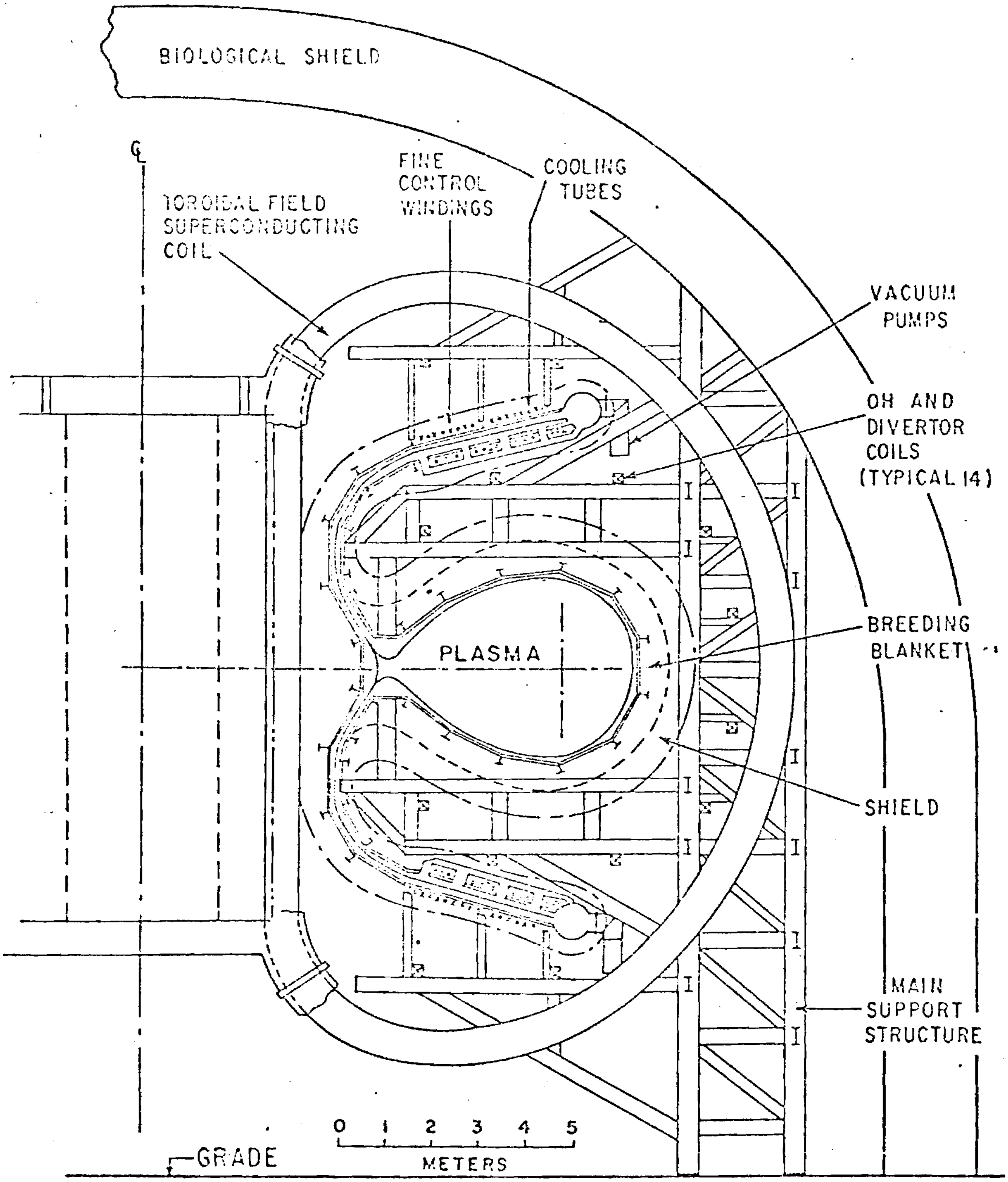

FIGURE 15. Princeton Fusion Reactor Design. Source: WASH-1239

were placed outside the neutron shield in order for them to be either superconducting or cryogenically cooled. The divertor windings also provide the vertical magnetic field that is necessary for plasma equilibrium. Furthermore, the size scale had to be sufficient to permit adequate neutron shielding between the reacting plasma and the superconducting toroidal field coils thereby limiting the heat deposition in the coils by the neutrons to acceptable levels.

In keeping with Item 3 above, stainless steel is the chief construction material. The vacuum wall is constructed of stainless steel plates welded on a steel framework. Liquid lithium is not used as a coolant to avoid associated MHD problems, but lithium in the form of flibe is used for tritium breeding. The blanket is cooled by helium gas which in turn is used to drive helium gas turbines.

The use of stainless steel limits the blanket operating temperatures to about 550°C. Thence the design foregoes the advantages of higher thermal cycle efficiencies that can be achieved with higher operating temperatures. However, the use of higher temperatures would require the use of a refractory metal, such as niobium, which is not in common use today.

The use of helium coolant has been proposed in several other fusion reactor prototypes.

New University Programs

In addition to the programs at Princeton and the schools listed previously, new university curricula reflect growing interest in nuclear fusion as an alternative energy source. At Georgia Institute of Technology, the School of Nuclear Engineering presently offers curricula in Thermonuclear Engineering. Work in progress includes fusion reactor neutronics calculations, advanced fusion energy conversion studies, and comparison of fusion power with alternate energy sources.

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FINAL REPORT

NASA Grant NGR-11-002-166

COMPARATIVE EVALUATION OF SOLAR, FISSION, FUSION, AND FOSSIL ENERGY RESOURCES

PART IV

ENERGY FROM FOSSIL FUELS

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This document is Part IV of a 5-part report entitled Comparative Evaluation of Solar, Fission, Fusion and Fossil Energy Resources, prepared under NASA Grant NGR-11-002-166 from the Lewis Research Center. George Kaplan is Technical Officer for this project.

FOSSIL FUELS: SUPPLY AND DEMAND

Each year the average person consumes about 4.4 million BTU's (MBTU) of energy in the food he eats, which is the amount of energy contained in about 340 pounds of coal. This is the minimum amount of energy required to survive. Energy consumption today in some underdeveloped nations is not much greater than this value. However, in the United States today per capita energy consumption is about 390 MBTU's, equivalent to 15 tons of coal per person, a 90 fold increase over the energy consumption of primative man. As shown in figure 1, coal accounts

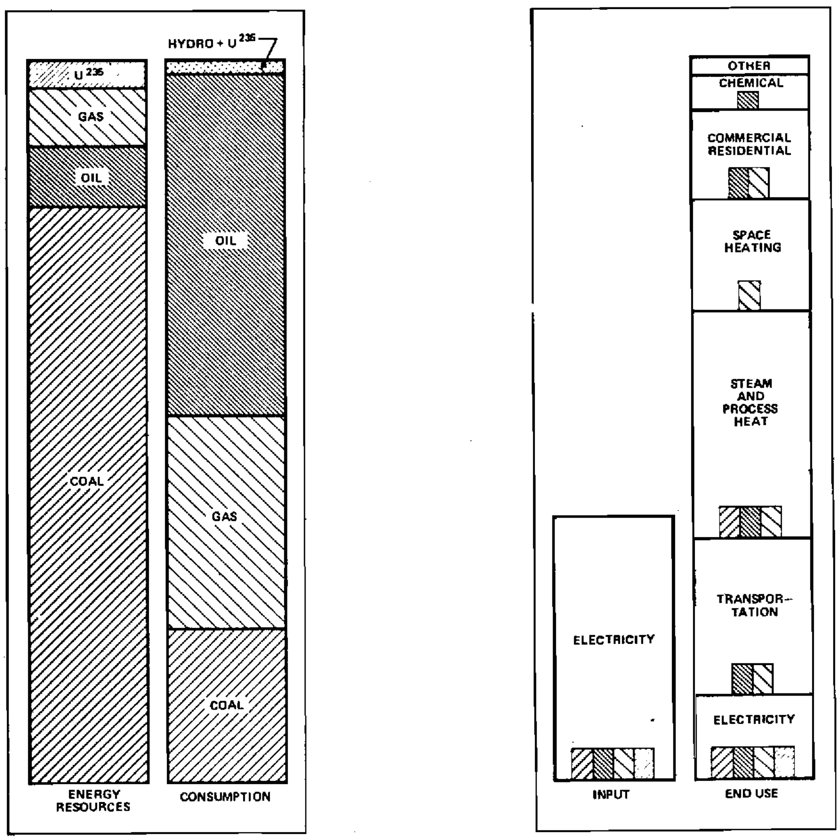

Figure 1. Comparison of Coal, Oil, Gas and U^{235} Resources and Uses[1]

for about 80% of the fossil fuel energy resources of the United States, gas about 10% and oil about 10%. However, gas and oil are being used much faster than coal. About 36% of these fossil fuels are used each year to generate electric power, which accounts for only 12% of our energy use, because of the energy lost as waste heat when fossil fuels are burned to produce electricity. Between 1900 and 1950, coal accounted for 65% of the fossil fuels used to generate electric power at central station plants. In 1971 this declined to 54%, and declined further with the enforcement of air pollution emission regulations prohibiting the combustion of high sulphur coal without expensive flue gas scrubbing equipment. However, the Arab oil embargo in 1973 and subsequent relaxation of air quality standards has caused this trend to reverse. States which permit the use of tall smokestacks for SO_2 control are continuing to rely heavily on high sulphur coal (up to 3% sulphur) for electric power generation[2], rather than use gas or fuel oil which are now much more expensive than coal.

Figure 2 illustrates the total world petroleum resources given in equivalent

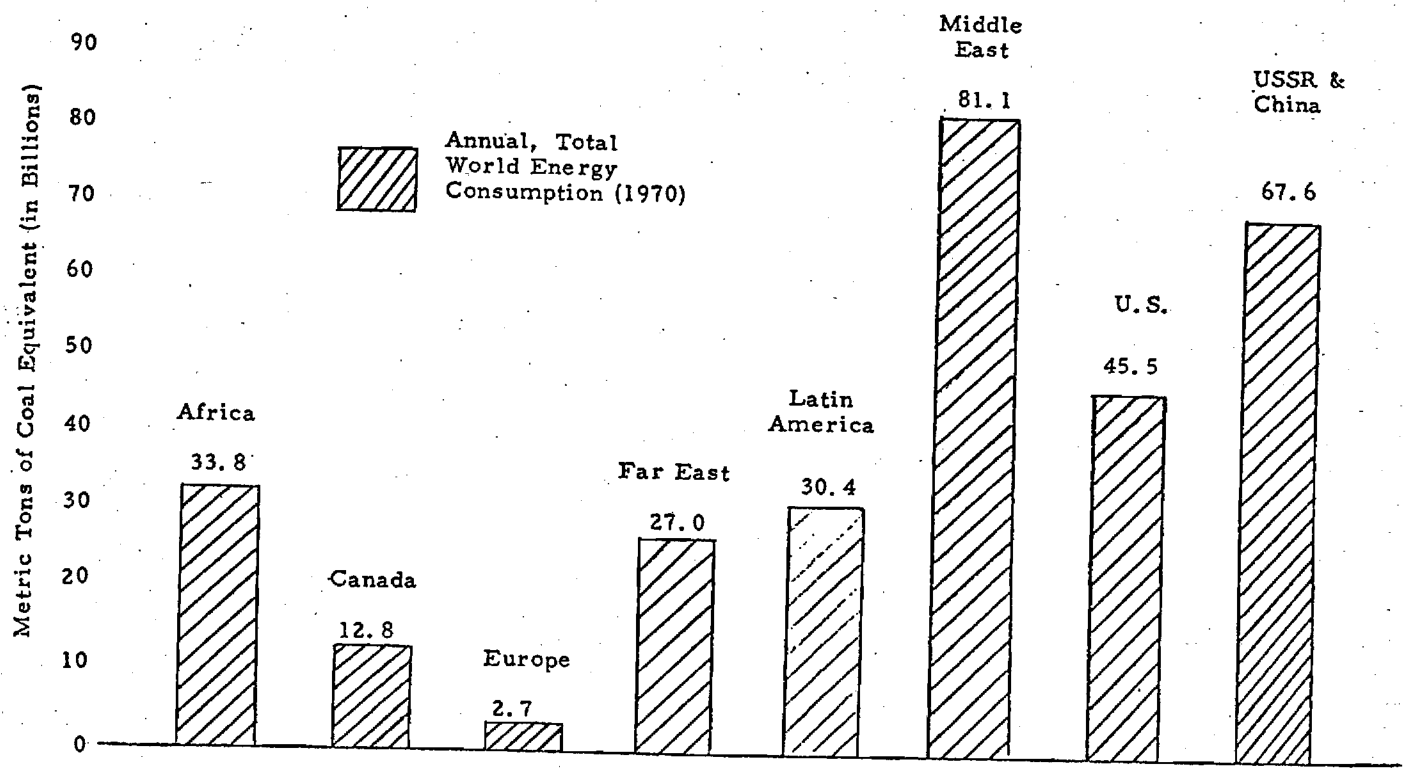

Figure 2. Total World Oil Resources[3]

metric tons of coal. Figure 3 gives the total world coal reserves. The total world reserves of oil is equivalent to 300 billion metric tons of coal, only about 4% of the total world reserves of coal which is given as 7637 billion metric tons. Figures for mainland China are very rough at present.

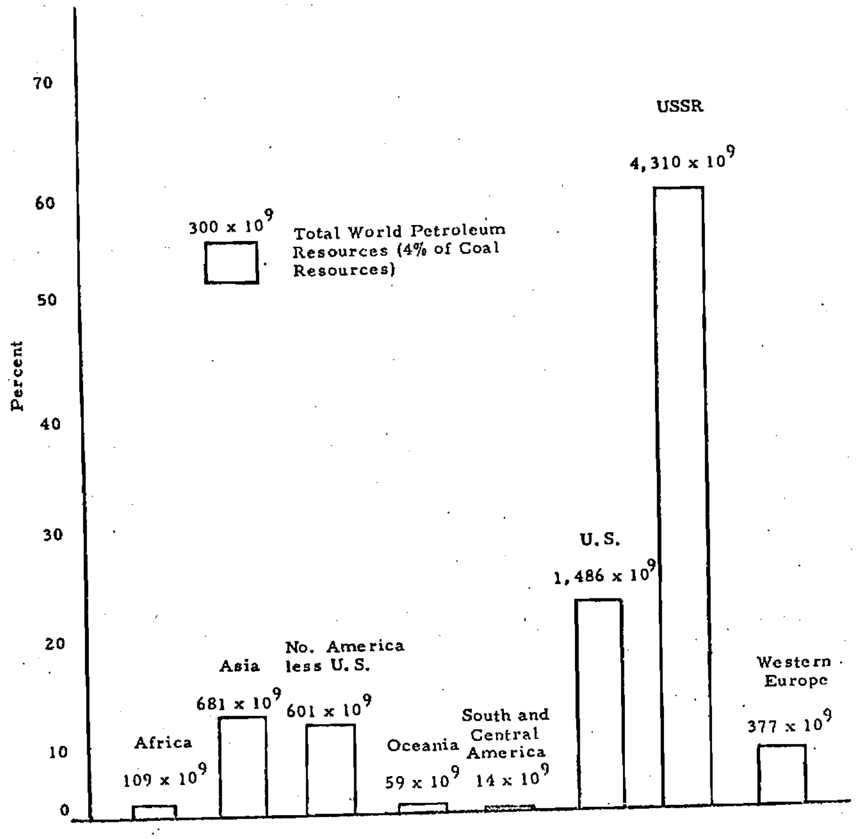

Figure 3. Total World Coal Resources[3]

The basis for the long term energy problem of the United States is illustrated by Table 1, which compares the United States annual consumption in 1970 with the proved recoverable fossil fuel reserves at that time[4]. Obviously, even at the 1970 rate of consumption, if the United States relied on domestic resources alone, the natural gas would be gone in 12 years and domestic oil would disappear in 7 years. However, these figures do not tell the whole story. The cost of

TABLE 1. Proved Recoverable Fossil Fuel Reserves and Annual Consumption - 1970

	Proved Reserves	U. S. Annual Consumption
Coal, U.S. (billion tons)	265	0.6
Gas, U.S. (trillion cu ft)	265	22.2
Oil (billion bbl)		
U.S.	37	5.5
Balance of free world	474	-
Communist bloc	100	-

extracting any of those resources increases as the resource becomes depleted, since the lowest cost deposits tend to be extracted first. Extraction cost is the big difference between the United States oil reserves (Figure 2) and the Mideast oil - extraction costs run about $0.25 per barrel in much of the Mideast as compared with several dollars per barrel in the United States.

Although the percentage of nuclear electric power generation is growing rapidly, the growth of nuclear power is not expected to reduce the demand for fossil fuels over the next two decades. Tables 2 and 4 illustrate projections by the Federal Power Commission made in 1970. The percentage of nuclear fuel use increases from 3% in 1970 to 55% in 1990 and the percentage of fossil drops from 97% to 45%, but the actual quantities of coal and oil use are expected to double. The main point here is that nulcear electric generation is not expected

Table 2. Projection of United States Generating Capacity[5]
(1 GW = 1000 Megawatts)

	1970		1980		1990	
	GW	%	GW	%	GW	%
Conventional Hydro	51.7	15.2	68	10.4	82	6.5
Pumped Storage Hydro	3.6	1.1	27	4	71	5.6
Fossil steam	260.3	76.5	393	59	557	44.6
Internal combustion and gas turbine	18.3	5.4	30	4.5	50	3.9
Nuclear	6.1	1.8	147	22.1	500	39.4
TOTAL	340.0	100.0	665	100.0	1260	100.0

Table 3. Electric Utility Power Generation-Thermal Generation by Types of Fuel[4]

	1920	1956	1960	1968	1969	1970
Coal	92%	70.8%	66.3%	61.9%	59.2%	58.0%
Gas	1%	21.7%	26.0%	27.6%	28.0%	28.0%
Oil	7%	7.5%	7.6%	9.4%	11.6%	12.0%
Nuclear	--	--	0.1%	1.1%	1.2%	2.0%

Table 4. Projected Fuel Use by Electric Utilities[5]

	1970		1980		1990	
	M TONS*	%	M TONS*	%	M TONS*	%
Coal	300.2	55	472.0	41.9	613.6	28.7
Gas	150.1	27.6	162.3	14.4	200.2	9.4
Oil	79.3	14.6	136.4	12.1	145.1	6.8
Nuclear	15.2	2.8	356.5	31.6	1176.1	55.1
TOTAL	544.8	100.0	1127.2	100.0	2135.0	100.0

*Fuel requirements here are expressed in equivalent tons of coal having a heating value of 25 million BTU/ton. M TONS = millions of tons.

to come in fast enough to reduce the consumption of coal, oil and gas for electric power generation. Of course, transportation, space heating, and industrial uses of energy are almost exclusively fossil fuels, especially oil and gas. Figure 8 of Part I of this report illustrates the switch from coal to fuel oil and gas for heating buildings. Our transportation systems rely almost exclusively on oil derivatives. Since the easily obtained domestic resources are gone and domestic reserves of oil and gas are rapidly running out (Table 1), the only alternative appears to be the importation of huge quantities of oil and liquified natural gas (LNG) from foreign countries.

Until very recently this appeared to be the solution to the energy problem. Since the Arabs were willing to sell us their oil at $1.80 per barrel, cheaper than we could extract it within the United States, continued supplies seemed assured. Japan and others built thriving economies on cheap foreign oil. However, economic pressures - the basic law of supply and demand - caused the price to rise to about $3.00/barrel, still a good price. Then came the Arab-Israel war of 1973 and the embargo and escalation of the price to over $11/barrel, twice the price of domestic crude in the United States. At this price, which threatens to go even higher, foreign oil is no longer the solution to the energy problem. Many projections have been made showing dramatic increases in oil imports to make up the deficit between domestic demand and domestic supply. These projections are pure fantesy. At today's prices, the United States simply cannot afford these imports. Such continued increases in imports are economically impossible. This is just as true for other western nations as it is for the United States.

With the rising price of oil and limited supplies of domestic gas and oil, the following approaches are being taken to reduce oil consumption and guarantee a continued gas supply.

1) Convert fossil-fired power plants now burning oil or gas to burn coal. Relax the air quality standards or use tall stacks to permit the combustion of high sulphur coal without causing the ambient air quality standards to be violated[2].

2) Develop coal-gassification processes to insure a continued supply of gas from coal.

Both of these measures increase the consumption of coal in order to reduce requirements for oil and natural gas.

The location of major crude oil producing areas, refining areas, and pipelines in the United States are illustrated in Figure 5. Figure 6 shows major natural gas producing areas and pipelines.

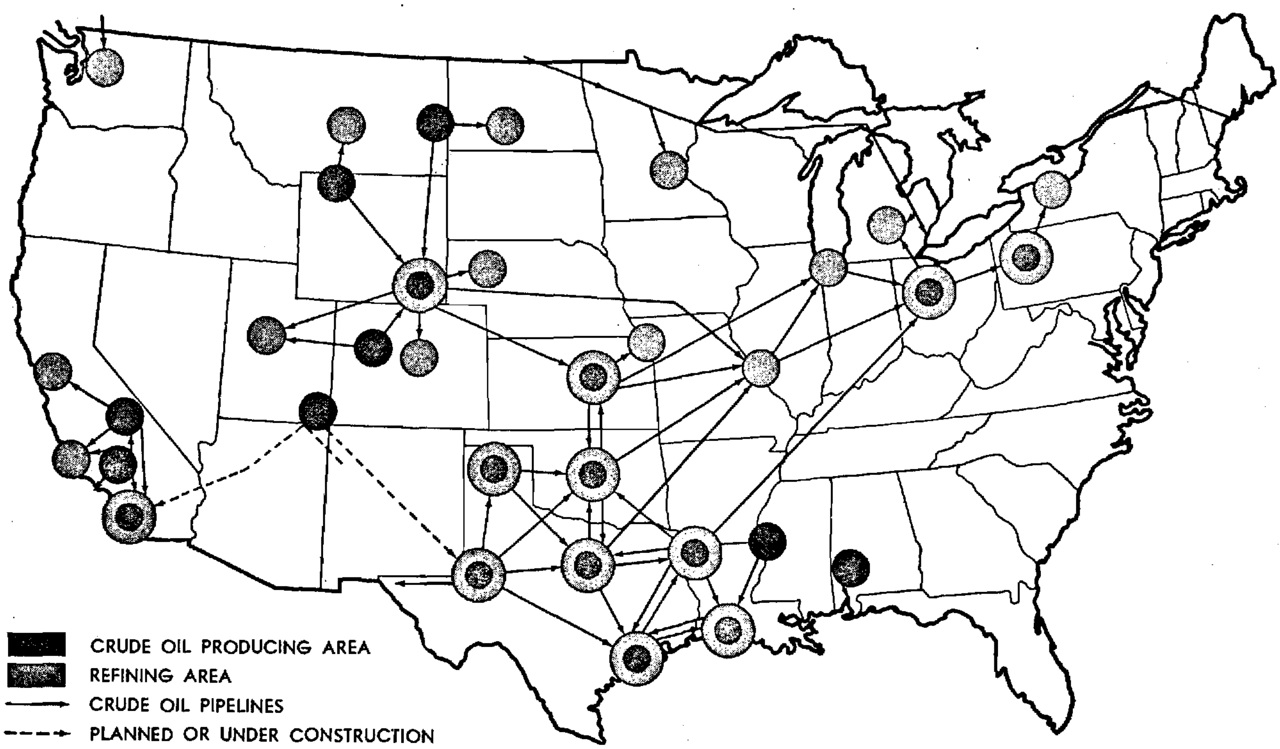

Figure 5. Oil Fields, Refining Areas and Pipelines in the United States[7]

Oil shale, a sedimentary rock containing organic matter, will yield oil when it is heated. Although the recovery of oil from shale has not been done on a commercial basis in the United States, it has been demonstrated on a small scale

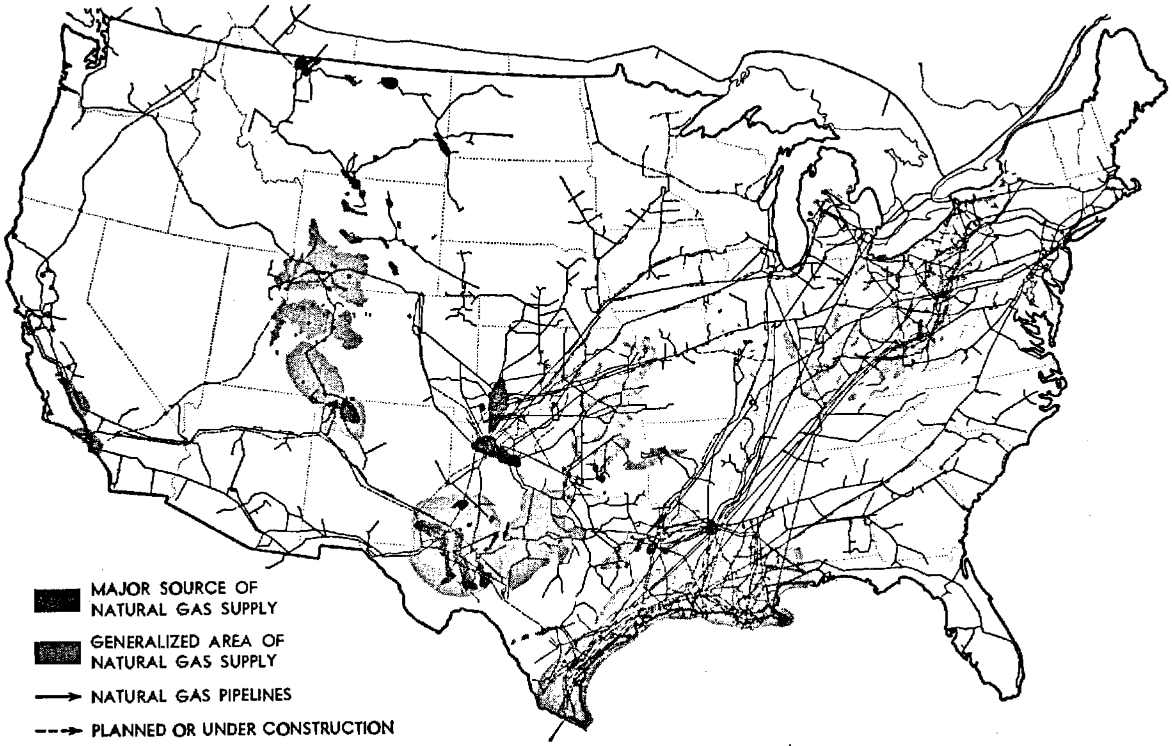

Figure 6. Natural Gas Fields and Pipelines in the United States[7]

that a range of acceptable fuel oils may be produced from shale oil by relatively simple refining techniques and that motor and diesel fuels can be produced by special refining methods. Since the yield of oil may be only 30 gallons per ton of shale, recovery of oil from this source involves handling large quantities of solid matter. The amount of domestic oil available from oil shale is about ten times the crude oil reserves in the United States[7], and greater than the oil reserves of the Mideast; however, the cost of extracting this oil is high and the environmental damage greater.

FOSSIL FIRED POWER PLANTS

Characteristics of New Plants

Schwieger[6] reported a survey of new fossil fired generating plants in 1971 and concluded that most new plants were operating with steam conditions above 2400 psi, 1000 °F (Figure 7). Turbine size and boiler capacity of the new plants

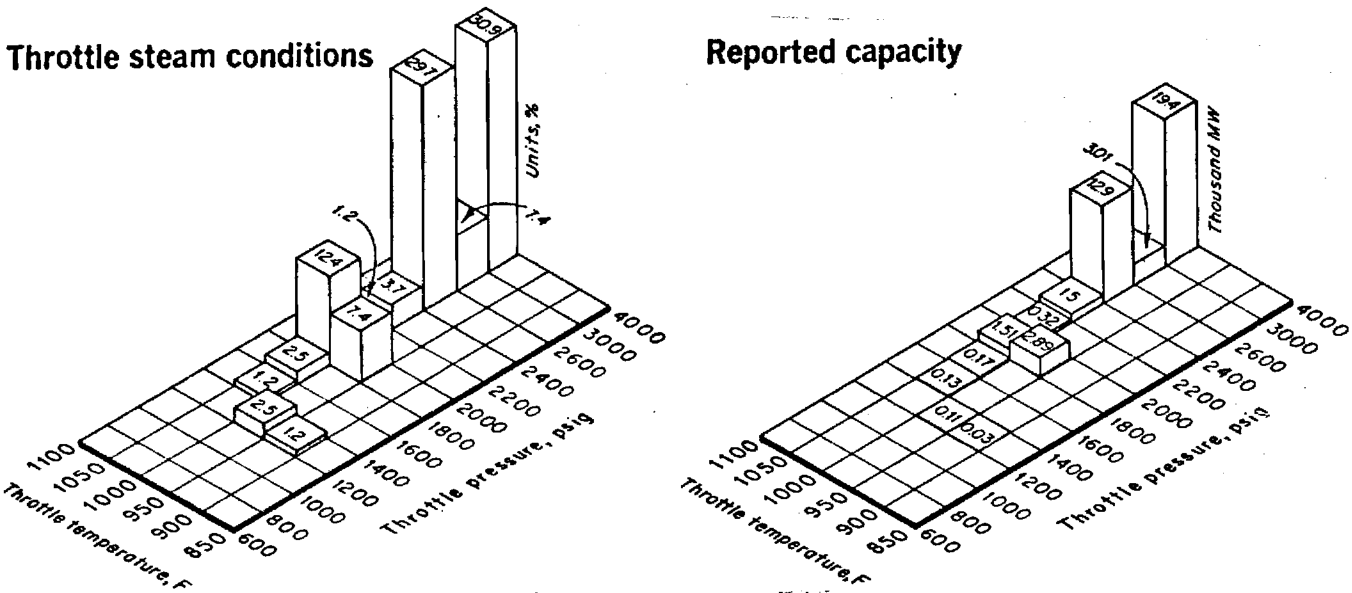

Figure 7. Steam Conditions of New Plants in 1971

are given in figure 8. Figure 9 shows the types of fuel used and other features of these new plants. The larger boilers use oil and gas.

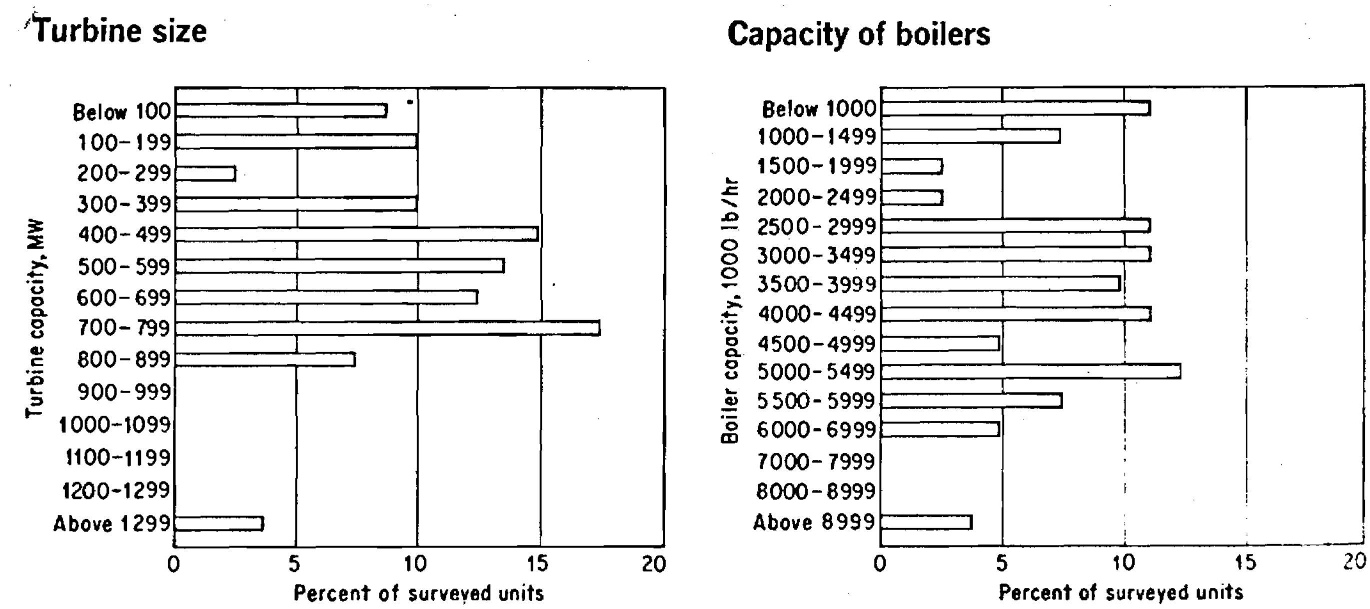

Figure 8. Turbine Capacity and Boiler Capacity of New Plants in 1971

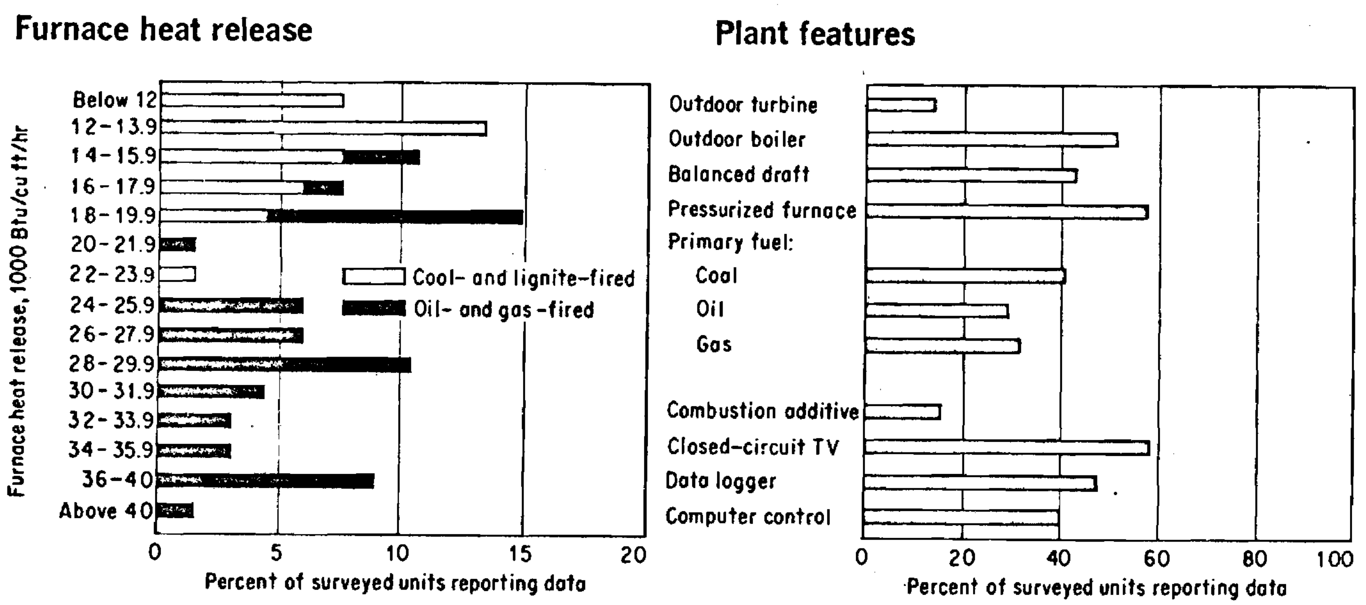

Figure 9. Heat Release, Fuels Used and Other Features of New Plants in 1971

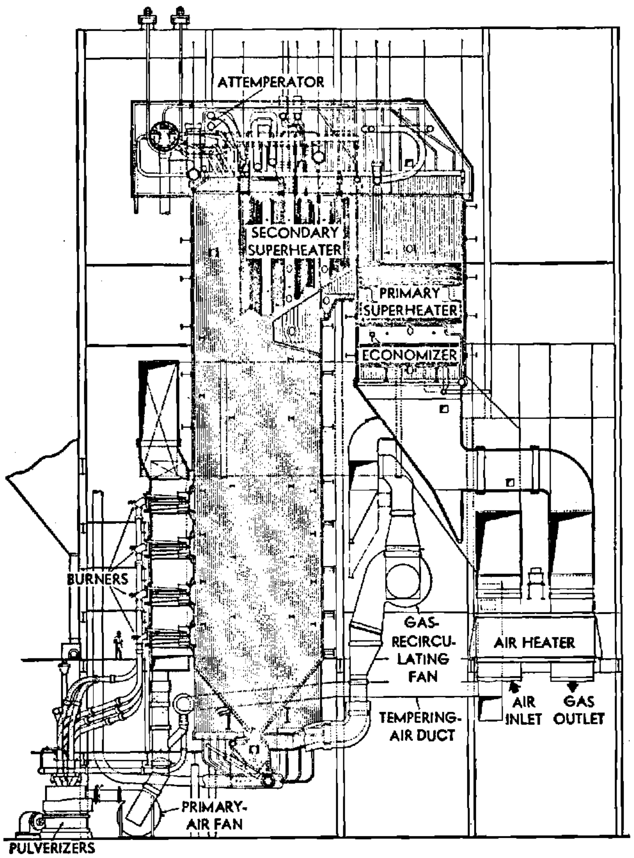

Figure 10. B&W Boiler for Providing 2.4 Million Lb/hr Steam at 2500 psi, 1050 °F with 1050 °F Reheat[7]

Technology

Figure 10 illustrates a modern fossil-fired boiler manufactured by Babcock and Wilcox, Inc.[7] Pulverized coal is blown into the furnace where combustion takes place. The wall of the furnace contains many boiler tubes; much of the heat of combustion is transferred to the water in the tubes, causing the water to boil to produce steam. The exhaust gases flow through the superheaters, then the economizer, then through the air heater, then through particulate (and perhaps SO_2) removal equipment, then up the stack. The air heater transfers heat from the exhaust gases to the air entering the furnace. In a well designed steam plant the exhaust gases may enter the stack at temperatures as low as 300°F. The boiler in Figure 10 produces 2.4 million lb/hr of steam at 2500 psi and 1050 °F with reheat to 1050 °F[7].

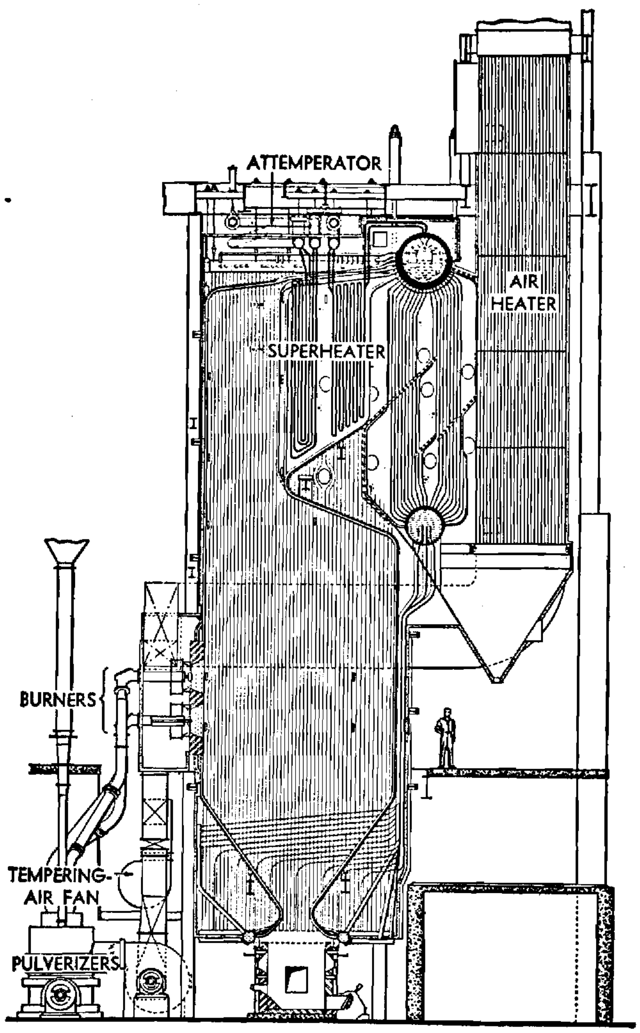

Figure 11. B&W Boiler (925 psi, 900 ^{o}F Steam)[7]

Figure 11 illustrates a smaller boiler for generating steam at lower temperatures and pressures.

A 4500 psi, 1150 ^{o}F steam supply system with two stages of reheat is shown in Figure 12. Few plants have been built operating at these steam conditions. This unit produced 120 MW_e.

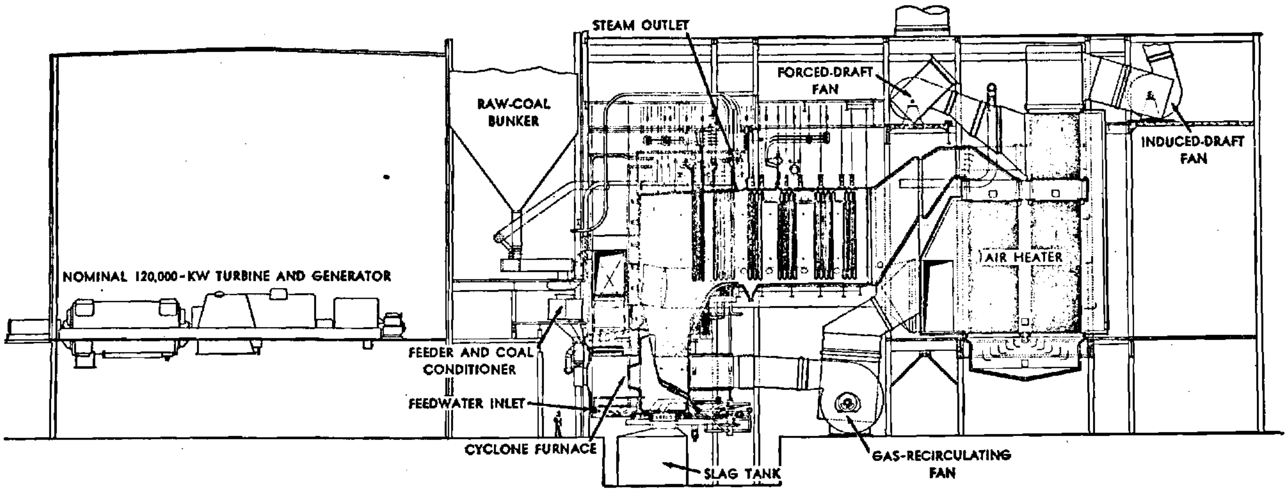

Figure 12. 120 MW_e Generating Unit with a B&W Boiler Operating at 4500 psi, 1150 °F with Reheats to 1050 °F and 1000 °F[7]

The fan circulates air or gas by means of a bladed rotor, or impeller, and a housing which collects and directs the gas discharged by the impeller. The power required by the fan is directly proportional to the volume of gas moved and the head (pressure difference) against which the gas is delivered, and inversely proportional to the efficiency of the fan and drive. Fans are used both for circulating air and gases in the plant and for blowing the exhaust up the stack. Stacks seldom provide the draft required by modern boilers, so fans are used to provide the required mass flow rate. Higher flow velocities up the stack also increase the plume rise, providing better dispersion of the effluent in the atmosphere.

There are basically two types of fans; the centrifugal fan (Figure 13) and the axial flow fan (Figure 14). The centrifugal fan accelerates gas radially outward by a rotor to a surrounding scroll casing. The axial flow fan accelerates the gas parallel to the fan axis.

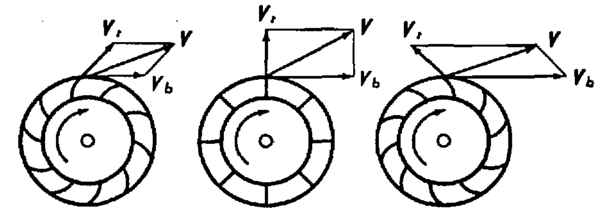

Figure 13. Three General Types of Centrifugal Fans[7]

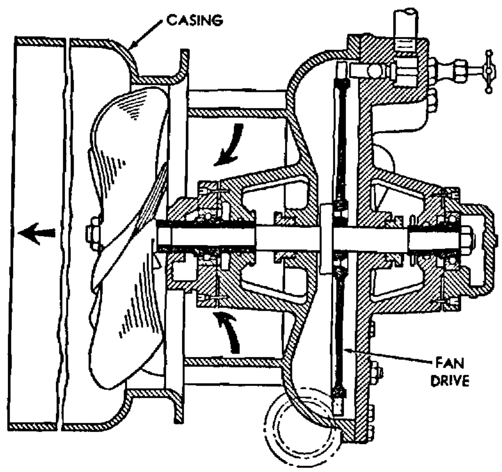

Figure 14. Simple Type of Axial Flow Fan[7]

Several techniques are used to vary the fan speed including magnetic coupling, hydraulic coupling, mechanical drive systems, variable speed d.c. motors, and variable speed steam turbines. The magnetic coupling uses two windings; a change in field strength between them carries the slip and the speed of the fan. Similarly, the hydraulic coupling (Figure 15) uses a variable thickness of oil to provide for variable slip.

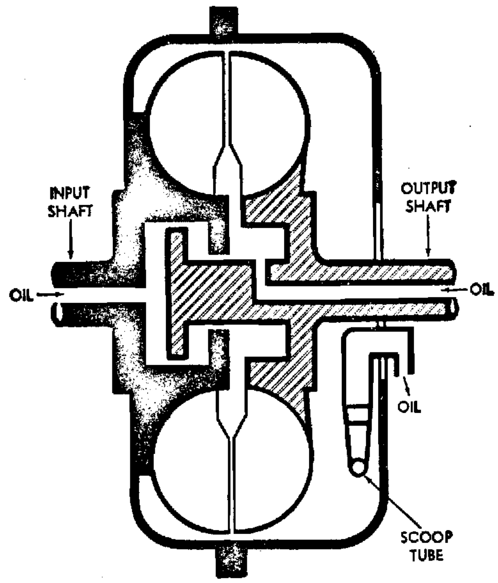

Figure 15. Hydraulic Coupling for Varying Fan Speed with Constant Speed Driver[7]

Two-speed AC motors are also used in connection with variable coupling devices to vary fan speed with minimal efficiency loss.

For higher pressure differentials centrifugal compressors can be used, of the type shown in Figure 16.

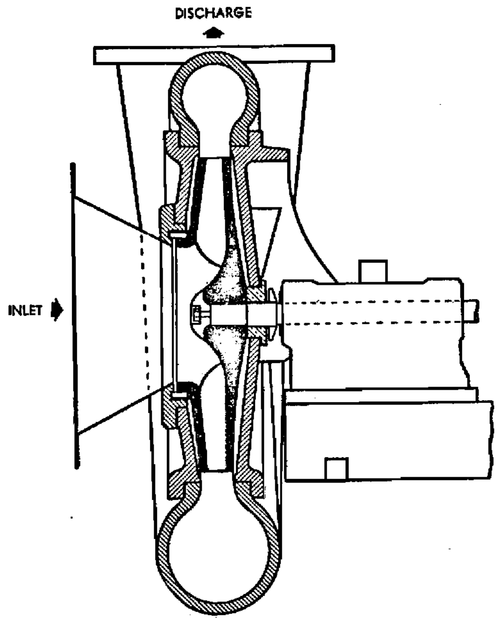

Figure 16. Centrifugal Compressor

The flow of gases through a down-fired boiler is shown in Figure 17. The combustion gases in the furnace are much hotter than the water in the boiler tubes; this large temperature difference is necessary for the high heat transfer rate in the boiler. The exhaust gas is somewhat cooler when it enters the superheater, but still several hundred degrees hotter than the peak steam temperature.

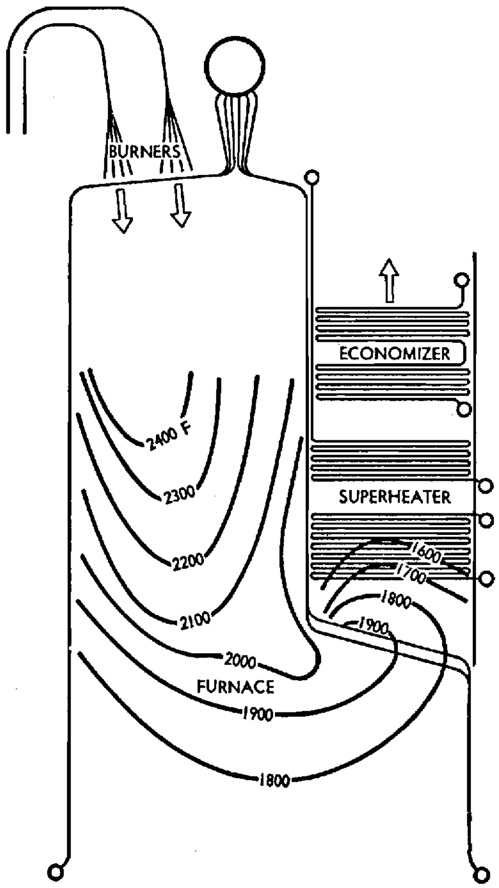

Figure 17. Temperature Profile of Combustion Gases in Down-Fired Boiler[7]

Air heaters transfer heat from the products of combustion to the air entering the furnace, so that this heat is recovered and the plant efficiency is increased. Tubular air heaters consist of a nest of straight tubes expanded into tube sheets and enclosed in a steel casing. The tubes are rolled into tube sheets at both ends with one sheet free to move to provide for expansion. The tubes are typically 2 to 2-1/2 inches in diameter. Five types of tubular air heaters are illustrated by Figure 18.

Another type of air heater, called the rotary regenerative air heater, uses slightly separated metal plates supported on a slowly rotating shaft. As the plates pass through the exhaust gas stream they are heated and then in passing

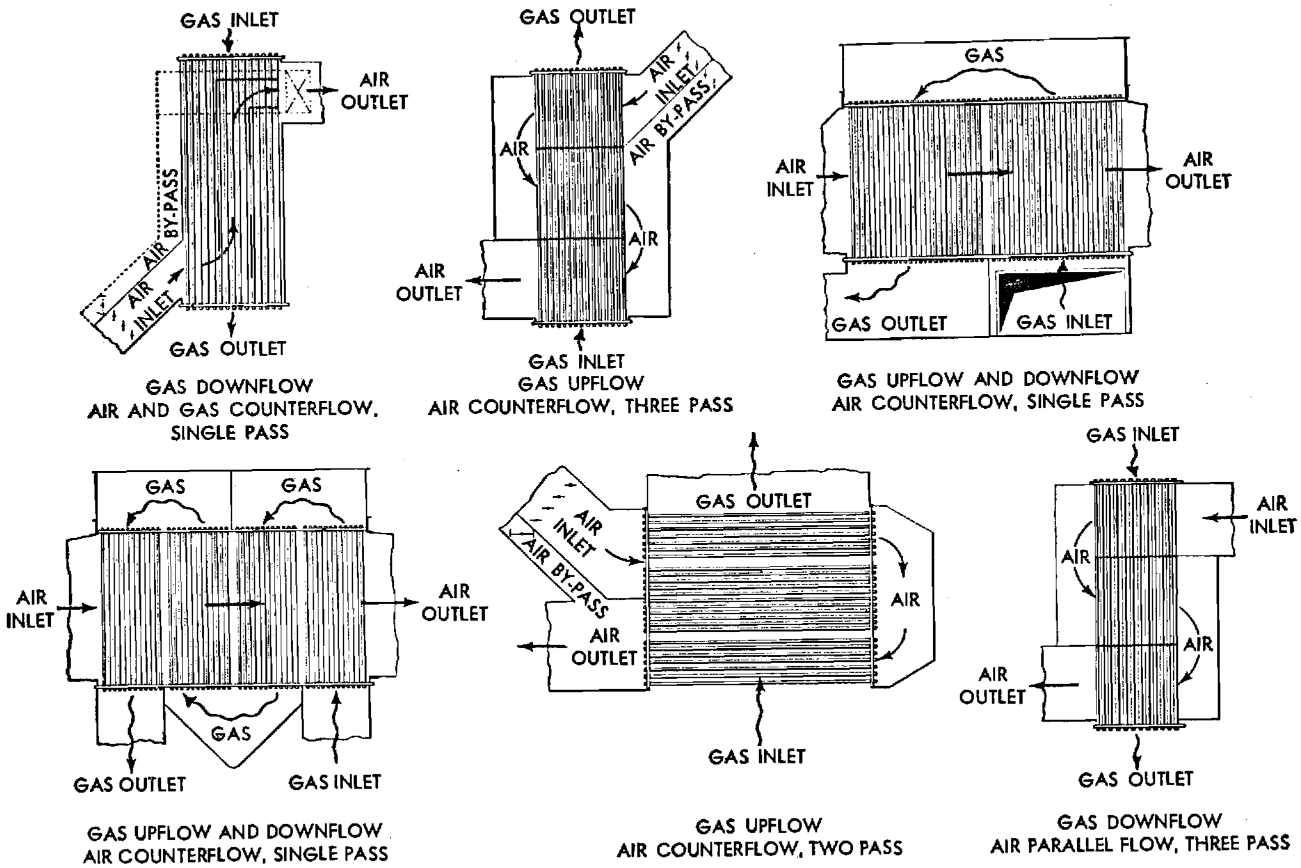

Figure 18. Five Types of Tubular Air Heaters

through the air stream they give up heat to the air before reentering the exhaust gas stream.

At the present time there appears to be no significant economic incentive to increase steam temperature beyond 1050 ^{o}F, so the most widely used steam conditions today for coal and oil burning plants are in the range of 1800-3500 psi with an initial temperature of 1000-1050 ^{o}F and single-stage reheat to 1000-1050 ^{o}F. One stage and, in a few cases, two stages of reheat are employed with a maximum temperature of 1050 ^{o}F[8].

Costs

Based on data from 42 modern power plants of 34,808 MW_e total generating capacity, the average capital cost for this fossil-fired generating capacity was

$\$123/KW_e$, the average load factor was 62.8%, and the average thermal efficiency was 34%. The total operating cost in 1970 averaged 3.48 mills/kw hr. These generating costs ranged from 2.16 mills/kw hr. for a large multi-unit station burning 21.6¢/million BTU gas to 6.73 mills/kw hr. for a smaller unit burning 41.8¢/million BTU coal[9]. Figure 19 illustrates the operating cost and capital cost of these fossil fired power plants. As is seen from the chart on operating costs, the cost of fuel accounts for the largest part of the operating cost of the plant. These fuel costs have risen sharply since 1970. In addition, costs of building plants have increased due to inflation.

In 1971 the annual rate of increase of construction costs was more than 12%, primarily due to the 17% increase in construction labor cost that year. This increase was due both to wage rate increases and productivity decreases. As reported by Roe[10] in 1972, "When both wages and fringe benefits are considered, workers in the construction industry today earn on the average between $6 and $10 per hour. Many of these workers also earn overtime. For example, for a 45-hour work week, many of the higher skilled trades such as steam-fitters and boilermakers today can earn a gross pay of $550 to $600 per week, or around $30,000 per year.

"Another factor of importance is a wide variation in construction wage rates throughout various areas of the country. Laborers' hourly wages vary from $4.40 in New Orleans to $8.81 in New York. Steamfitters' hourly wages vary from $8.40 in Denver to $11.54 in Los Angeles.

"Another significant contributor to increasing construction labor costs is a decline in productivity. Overall statistics for the construction industry indicate that output per man-hour increased approximately 1-1/2% per year during the twenty-

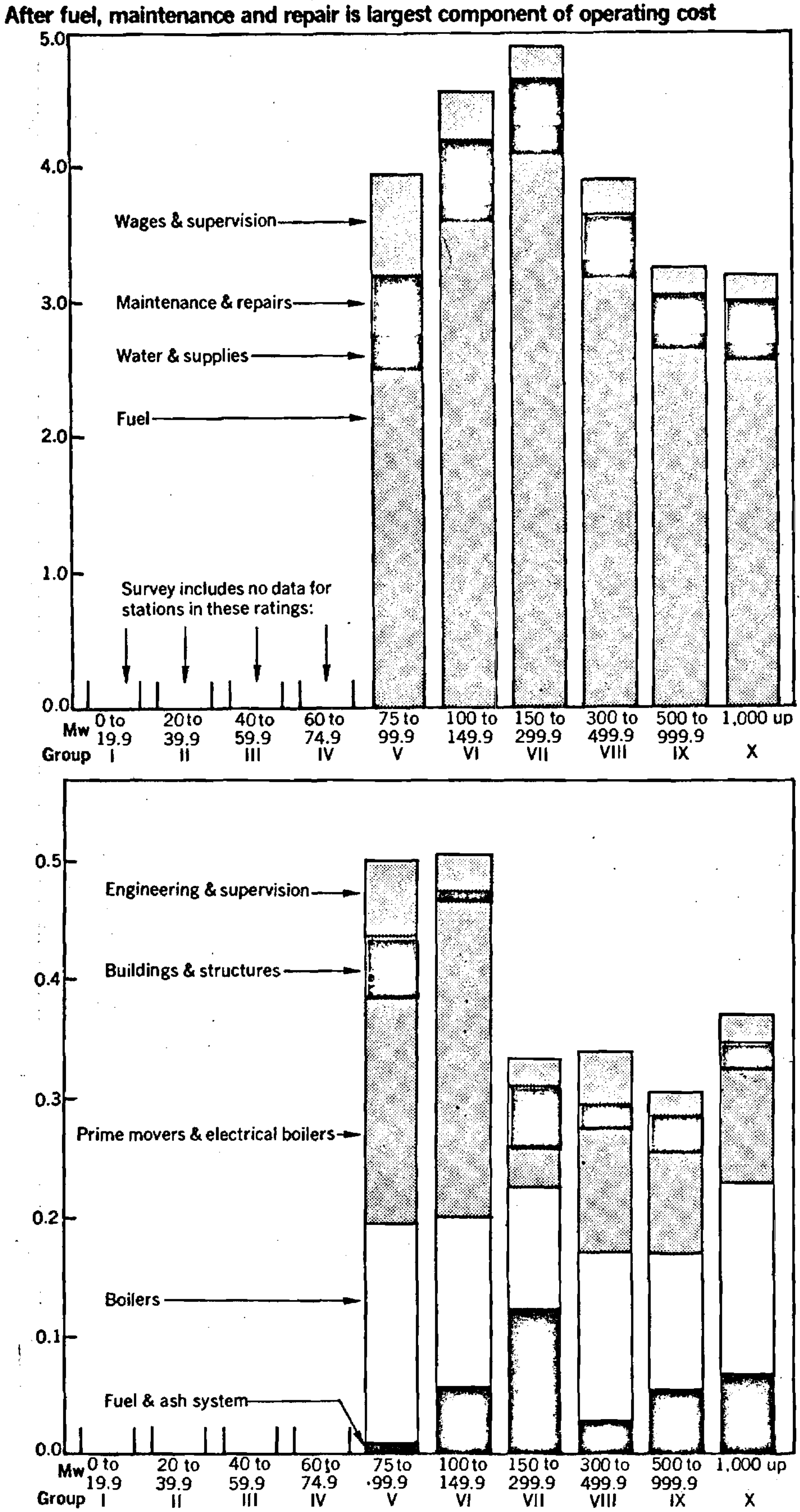

Figure 19. 1970 Operating and Captial Costs of Fossil Plants[9]

year period between 1947 and 1967. This rate of increase was well below that of most other industries. Careful examination shows that this output increased through advances in equipment technology and use, not through increased labor productivity. The rate of overall productivity improvement in this country declined in the late 1960s. There appears to be clear evidence that productivity has actually decreased a great deal in the construction industry.

"On many power plant construction projects today, the trend has been toward very liberal use of overtime to try to meet schedules and to provide incentives to attract labor to a particular project work location. The use of overtime can add tens of millions of dollars to the cost of a generating plant, frequently with questionable long-term improvement in schedule. A study of the use of overtime in the construction industry was performed for the Construction Users Anti-Inflation Round Table. It was found that a 50-hour work week over periods of four to six months boosted labor costs 50% while producing little if any extra output. Therefore, overtime should be resorted to only where there is no alternative.

"In recent years, equipment and material costs, which have traditionally comprised up to 60% - 80% of power plant construction costs, have generally increased at rates of 4% - 10% per year. The increases occurred for a number of reasons such as wage increases, increased quality requirements, and higher interest rates."

Other factors increasing costs are schedule delays, and new requirements for pollution control equipment which can add $50 million or more to the cost of a fossil plant. Roe[10] expects the capital cost of fossil-fired plants to rise as high as $400/KW$_e$ by 1980.

GAS TURBINES

The electric utility industry is now using gas turbines extensively because they can be installed quickly to provide needed capacity. The new larger gas turbines of more than 50 MW_e rating, with their improved efficiency, are proving valuable for peaking service. The basic characteristics of short shipment cycle and low installed cost has been crucial to customers suffering from low peak load forecasts, long nuclear delays, or poor reliability of new large units.

Two types of mid-range gas turbine plants are the regenerative cycle gas turbine, and the combined cycle STAG (acronymn meaning Steam and Gas) plant. Each has its own unique advantages for specific utility systems.

Until recently, there was little industry interest in mid-range generation. The typical utility load duration curve was essentially supplied according to the age of the power sources. The latest large plants having the best efficiency supplied the base service at load factors of 80-90 percent. The middle part of the curve was covered by older plants with poorer heat rates at load factors of 20-80 percent. Plants for peaking duty were the very oldest steam plants with 12,000 to 20,000 BTU/Kw hr heat rate. This system has worked for quite some time, as the plants being ordered were basically much better versions of the same type of power source - fossil steam turbines. Sizes continued to increase and heat rates continued to decrease.

Recent changes, however, have forced changes in this approach. Rather than continuing to buy the same type of plant, utilities have seen the value in very large nuclear and fossil steam plants for economical base load generation. At the same time peaking requirements have sharply increased to meet escalating peak load trends, combined with decreasing system load factors. No longer does a system's oldest units have either the characteristics or the total power to supply this peak load. Recently large numbers of gas turbines have been ordered to supply this need. Thus recent history has tended to divide power systems into two separate power sources, gas turbines and very large base load units, each ideally suited to its special purpose. In between these two lies mid-range service. As before, the older fossil units are supposed to fill this need. But present day needs are making this service difficult. The absolute size of the most modern base load units places added emphasis on mid-range units during scheduled maintenance outages. Unfortunately, lower availability of the large plants has increased each system's total mid-range power requirement. At the very time these older units are being asked to shoulder this added burden, with their inherent characteristics of poor load swing capability, long starting and stopping cycles, and poor part load performance, they are being hardest hit for their air pollution. For the future, these fossil units must continue to operate until they reach retirement age. But they must be supplemented now, and replaced later, by power plants intended for mid-range service.

Regenerative Gas Turbines

The regenerative cycle gas turbine is essentially a simple cycle gas turbine modified to make more efficient use of the available energy. It accomplishes this by using the heat of the turbine exhaust to preheat the air leaving the compressor just before it enters the combustion chambers. This preheating, of course, reduces the amount of fuel required to raise the air temperature to the desired turbine inlet temperature. The reduction in fuel consumption lowers the plant heat rate by over 2000 BTU while reducing the net plant power output only slightly. Table 5 lists the output and heat rate for simple cycle and regenerative cycle machines operating on three different fuels: gas, distillate, and residual oil.

TABLE 5

CYCLE	FUEL	NET OUTPUT (KW) BASE	NET OUTPUT (KW) PEAK	NET HEAT RATE (BTU/KW-HR) (HHV) BASE	NET HEAT RATE (BTU/KW-HR) (HHV) PEAK
Simple	Gas	45,800	53,300	13,460	13,220
	Distillate	44,800	52,100	12,980	12,790
	Residual	40,800	45,900	12,800	12,500
Regenerative	Gas	44,800	50,400	11,100	10,640
	Distillate	44,000	49,500	10,720	10,270
	Residual	38,800	43,500	11,200	10,670

The regenerative cycle gas turbine, then, is basically a significantly more efficient machine than the simple cycle, and accomplishes this without sacrificing any of the simple cycle units' advantages. Except for the additional air piping, it is the same compact, packaged unit. It thus has a short shipment schedule, minimal installation labor, and short installation time to cut down interest-during-construction costs. Combining its small land area requirement with the latest advances in both air pollution control (no visible smoke) and acoustic design will allow optimum utilization of this unit's self-sufficiency to reduce transmission costs. This plant is completely independent, requiring no cooling water or auxiliaries and is capable of remote operation and black starting. Remote unattended operation, no water, no smoke, and minimum space requirements, and esthetic appearance, allow properties such as substations and existing plant sites to be used. This can result in significant savings in site development and transmission costs.

Since the regenerative cycle machine uses the standard simple cycle unit as a base, and adds a time-tested regenerative unit with no untried developmental problems, it has high availability. It makes no compromises on the simple-cycle unit's fast, low-cost starting ability. The unit provides good part-load performance by using variable inlet guide vanes designed to reduce the air flow at part load in order to maintain a constant exhaust temperature, thus allowing a constant efficiency down to 83% load. This feature actually results in almost a 1000 BTU additional heat rate improvement for loads below 83% over the simple cycle performance.

The modular construction of the regenerative cycle design allows great latitude in plant size flexibility, both in the definition of initial plant size, and in the capability for future additions. The 50,000 KW range unit size permits load carrying flexibility, spinning reserve capability, and low reserve margin requirements unattainable by large fossil plants, while forcing no limitation on maximum plant size.

The regenerator itself is a very simple component, with no moving parts. The regenerator is built in two sections, one on each side of the gas turbine. The gas turbine exhaust splits and flows through the regenerator after which it is turned upward and discharges to the atmosphere. By splitting the regenerator in two sections the piping is symmetrical and the top half of the turbine can be removed without disturbing the regenerator piping.

The air from the compressor passes through an integral manifold system into a number of tubes. This air passing through the tubes is heated by exhaust gases flowing on either side of the air channels in the opposite direction. The air is then collected in a second manifold and discharged to the outlet piping where it is then conducted to the combustion chambers.

The regenerator is of bar and plate construction. This design allows maximum utilization of the available heat transfer surface and results in a compact unit. An exhaust gas tube consists of a copper brazed and welded envelope with internal corrugated extended surface. Copper brazing the extended surface to the tube sheets results in a thermal bond of maximum heat conduction. Structural reliability is assured by preloading the bond in compression.

A tube bank consists of a number of these tubes, separated by spacers, and welded to form an integral unit. The passages for the compressor air are thus formed by the spacers between the exhaust gas tubes. The regenerator assembly is completed by manifolding the number of tube banks required for the rated air flow.

Combined Cycle

Higher efficiency is achieved by effective use of the energy wasted in the form of heat in the exhaust. The regenerative cycle unit uses this heat to raise the temperature of the compressor air. In the steam and gas turbine STAG plant the exhaust is used to make steam in a heat recovery boiler. This steam then drives a steam turbine. Table 6 lists parameters for two plants sold by the General Electric Company.

TABLE 6

PARAMETERS OF TWO STAG PLANTS

PLANT	FUEL	(KW) BASE	PEAK	NET HEAT RATE (BTU/KW-HR) (HHV) BASE	PEAK
STAG 330	gas	307,300	336,700	9110	8760
	distillate	303,400	331,800	8750	8430
	residual	286,300	306,200	9080	8750
STAG 180	gas	168,000	182,700	9100	8850
	distillate	165,900	180,200	8790	8570
	residual	159,500	167,500	9140	8850

To the gas tubines are attached heat recovery boilers. A bypass stack and damper are provided between gas turbine and boiler to allow peaking operation of any or all gas turbines apart from the rest of the system. All dampers, boiler controls, supplementary firing burner controls, and retractable soot blower controls (if needed), as well as controls for the gas turbines and steam turbine, are remotely located in a central control house.

The steam turbine for the STAG 330 is a GE tandem compound, double flow, non-reheat steam turbine with 23 inch last stage buckets. Again, in steam turbine design, packaging and standardization play key roles. For example, the downward exhaust has been replaced by side exhausts to twin condensers. As a result, the turbine can be factory assembled and shipped complete. The condenser elements can be factory tubed and shipped completely assembled.

The balance-of-plant electrical and mechanical hardware is also arranged in a manner allowing for minimum installation cost while still providing the necessary operational flexiblity. For example, provisions are included for dual sources of auxiliary power: one from the station bus and one from a separate outside source. The plant output is available through three separate step-up transformers and associated circuit breakers, one for each pair of gas turbine generators and one for the steam turbine generator. The mechanical accessories include two half-sized boiler feed pumps, two half-sized circulating water pumps, two full capacity condensate pumps and a steam bypass arrangement for plant startup.

Control of the STAG plant is designed for optimum mid-range operation. Most efficient operation requires control between the maximum output points for different numbers of gas turbines in operation. This plant is controlled as a single power source, not as a combination of five different sources, for mid-range service. Two men operate the plant from a master station control console located in a central control house. (Use of a high-salt, high-metal residual fuel would require an additional man for the fuel analysis, washing, treating, and transfer system.) Maximum automation has been incorporated in all start-up and load change sequences. A load change is actuated by the operator through a manual movement of a single load selector.

The STAG plant, then, is quite different than the regenerative cycle plant, yet offers advantages for mid-range operation. It has a low heat rate (high efficiency) rivaling fossil steam plants in its size range. The package concept using tried and proven components assures high availability. The plant is designed for fast starting. After a 12 hour shutdown, the plant can be brought to full load in 45 minutes. Even in a completely cold start, more than half the rated output can be available within 20 minutes, with full load in 150 minutes. Plant control design assures excellent part load performance.

The plant is designed to require a minimum number of operators: one at the control console, and one roving inspector (unless one man is needed for fuel treatment).

STAG can be in commercial operation two years from the placement of an order. Due to maximum packaging, installation time is less than six months after the arrival of the major equipment at the site.

The plant has complete black start capability. Water requirements are only 40% of those for a similarly rated fossil steam plant. This feature, plus the no-smoke combustion in the gas turbines assure minimal air and water pollution.

While the overall plant control has been emphasized, the composition of the plant allows peak load pick-up by operating any number of the gas turbines alone - an important feature.

Each of the mid-range plants discussed above has its own unique advantages. They are completely different concepts in mid-range plant design. The optimum plant selection for a specific time in a specific utility system requires the analysis of a number of economic questions. These are reviewed below.

Costs

The mid-range plants that have been discussed have their own characteristics which will be reflected in their long-term costs. Any analysis of the costs of alternative power plants must be based on several major assumptions. The need for a given plant is a function of the entire generation presently in operation on a system. All alternative plants must be judged on the same type of operation and load factor.

The costs given here included the cost of the basic plant and required options. To this is added installation costs, cooling water costs where required, fuel treatment costs where necessary, and interest during construction. A capitalization rate of 15% was assumed. Neither transmission costs nor system reserve differentials were included. These could vary substantially between systems. Fuel storage costs and system electrical equipment beyond the 13.8 KV breaker were not included, but are essentially equal for all machines. All costs are for mid-1972 commerical operation.

The installed costs for the simple cycle, regenerative, and STAG units for three fuels are shown in Table 7.

TABLE 7

PLANT INSTALLED COST

($/KW AT PEAK RATED NET OUTPUT)

	Gas	Distillate	Residual
Simple Cycle	85	87	107
Regenerative Cycle	105	107	130
STAG	119	121	135

Operating costs for these machines include fuel cost, labor, and maintenance. For this evaluation fuel costs of $\$.40/10^6$ BTU for natural gas, $\$.80/10^6$ BTU for #2 distillate oil, and $\$.40/10^6$ BTU for residual oil were used. No operators were assumed for gas or distillate fuels for the simple and regenerative cycle machines, and one man to handle fuel treatment equipment for residual oil. Two operators are needed for the basic STAG unit, plus one additional for fuel treatment of residual oil. Maintenance costs can be accurately estimated based on 20 million hours of gas turbine operating experience.

For natural gas, the simple cycle unit is most economical at low operating hours. The regenerative and STAG machines do not better the simple cycle unit until almost 3500 hours per year. In the mid-range area, between 2000 and 5000 hours, the differences between utility systems could favor any of the three machines. With the distillate oil, which is twice as expensive as gas, the breakeven point is at one half the gas breakeven time. The very efficient STAG unit is the clear favorite for long operation, unless cooling water or transmission limitations are governing.

For residual oil, the breakeven point is at 2000 hours, with the regenerative unit significantly poorer than STAG. This difference is largely a function of the proportionately higher fuel treatment costs for the regenerative unit.

The differences that can result from individual utility requirements must be emphasized. Each system should be evaluated separately.

The rapid increase in gas turbine purchases is illustrated by Table 8.

TABLE 8

UNITED STATES PUBLIC POWER SYSTEMS PLANT
ADDITIONS AND IMPROVEMENT

Type of Generation	$ Expenditures (millions) 1970	1971
Fossil-Steam	305	321
Gas Turbine	18	59
I.C. Engine	19	36
Hydro	85	80
Nuclear	204	299

Projections to 1980 indicate that it is possible that 6 to 10% of the total 600,000 MW_e capacity could be fossil fired gas turbines.

In the 1971-72 period the installed costs ranged from about \$60/KW_e to about \$85/KW_e for simple gas turbines, to \$105/KW_e for 50 MW_e regenerative plants, to \$125/KW_e for 330 MW_e combined cycle (STAG) plants[11].

COAL GASIFICATION

The manufacture of both substitute natural gas (SNG) and low-Btu gas from coal has become a subject of increasing interest in recent years-SNG because of the decline in natural-gas reserves and low-Btu gas because of the potential demand for clean fuel gas to meet environmental goals in the generation of electric power. Many coal-gasification processes have been used in the past to generate low-Btu producer gas or water gas. These processes generally operate at atmospheric pressure and do not represent economically feasible routes to high-Btu gas. The only commercially available high-pressure process for coal gasification is the Lurgi process. The commerical use of the Lurgi process that comes closest to SNG manufacture is that in which town gas, which has a heating value of 400 to 450 Btu/scf, is produced. One such installation is at the Westfield plant of the Scottish Gas Board[12]. There are numerous other coal-gasification processes being developed today. Most of the more widely known developments are being sponsored by the U. S. government or by government-industry groups.

Table 9 lists the major coal gasification processes. There are three basic steps in each of these processes: local preparation, gasification, and raw gas upgrading. The preparation phase includes handling, storage and size reduction of the coal. Some processes also require air oxidation of the coal in a fluidized bed at 600 to 800 ^{o}F and low pressure to drive off some of the volatile matter and render it nonagglomerating for the gasification process. The gasification step includes the chemical reactions which produce gas; these reactions are about the

TABLE 9

SUMMARY OF BETTER-KNOWN COAL GASIFICATION PROCESSES[13]

PROCESS NAME	DEVELOPER	Heat Input	Pressure, psig	Reactor type	Status
Lurgi	Lurgi	oxygen	300-500	downward moving-bed	near demonstrated
HYGAS oxygen	IGT	oxygen	1000-1500	fluidized	80-ton/day P.P. constructed
BI-GAS	BCR	oxygen	1000-1500	entrained/ slagging	will build 120-ton/day P.P.
Synthane	BOM	oxygen	600-1000	entrained/ slagging	will build 70-ton/day P.P.
Kellogg	Kellogg	O_2/air	400-1200	molten salt	have bench-scale data
CO_2-acceptor	Consol	air	150-300	fluidized (dolomite)	40-ton/day P.P. constructed
COGAS	FMC	air	50-200	entrained/ fluidized/ slagging	have bench-scale data
HYGAS electrothermal	IGT	electrical	1000-1500	fluidized	80-ton/day P.P. constructed

same for all the different processes. However, there are important differences in the method of feeding coal to the reactor system, in the reactor configuration itself, and in the method of supplying the heat needed for the gasification reactions. For simplicity, only four basic reactions are shown.

$$\text{coal} + H_2 \rightarrow CH_4 + C \qquad (1)$$

$$C + 2H_2 \rightarrow CH_4 \qquad (2)$$

$$C + H_2O \rightarrow CO + H_2 \qquad (3)$$

$$C + O_2 \rightarrow CO_2 \qquad (4)$$

First, the coal pyrolyzes, and much of the volatile matter is cracked and hydrogasified to methane and smaller quantities of higher hydrocarbons. Second, some of the char that remains can react with hydrogen to form additional methane. This reaction is very exothermic, but for most of the processes currently under development, the extent of reaction 2 is not sufficient to balance the very endothermic heat of reaction 3. In reaction 3, steam is the gasifying agent for the carbon, and the products are carbon monoxide, hydrogen, and smaller quantities of carbon dioxide. From a material-balance standpoint, reaction 3 is necessary because the coal is deficient in hydrogen (relative to the hydrogen content of methane); the additional hydrogen is supplied from water through the steam-carbon reaction. In almost all cases, the necessary heat input to the system is achieved via reaction 4 in which char is reacted with either oxygen or air to produce carbon dioxide or carbon monoxide. When air is used, the nitrogen-containing flue gases must be prevented from mixing with the raw gas produced in the gasification reactors.

The raw gas has a higher heating value of about 300 to 500 Btu/scf (dry basis). This gas contains methane, carbon monoxide, hydrogen, carbon dioxide, hydrogen sulfide, ammonia, and unconverted steam. The raw gas is upgraded to SNG in a series of steps common to almost all the processes. In shift conversion, the carbon monoxide-to-hydrogen ratio is adjusted for the later methanation step by reacting some of the carbon monoxide with steam to produce hydrogen and carbon dioxide. A second step is the removal of carbon dioxide and hydrogen sulfide from the raw product gas. Finally, carbon monoxide and hydrogen in the approximate ratio of 1 to 3 are reacted over a methanation catalyst to produce additional methane.

After the methanation step, the heating value of the SNG is in the range of 900 to 1000 Btu/scf.

The Lurgi Process

The Lurgi process could provide fuel for a power plant that combined the Lurgi process with a gas turbine.

Coal is introduced in the top of the gasifier after having passed through a crusher and a pressurized hopper. Air and steam are introduced through slots in the grating at the bottom of the gasifier. The oxygen in the air combines with coal in the combustion zone to form CO_2. Simultaneously coal is using the energy given off by combustion to react with steam to form CO and H_2. The endothermic reaction of C and H_2O keeps the temperature down. As the gases pass upward some carbon dioxide reacts with the coal to form carbon monoxide and some methane is formed. The fresh coal introduced in the top undergoes successive drying, devolitization and reaction with oxygen and steam. The volatile fraction of the coal cracks to form methane, hydrogen and other light hydrocarbons. The gasifier efficiency is approximately ninety-five percent with losses due to unburned material and some heat losses.

The crude gas contains sixteen percent CO, twenty-five percent H_2, and five percent CH_4. The gas is under approximately twenty atmospheres pressure and requires purification before it is ready for a gas turbine. The gas is under pressure and because of this it can be completely cleansed of solids (1-2%) by a quenching wash with hot water containing tar. The dust contained in the gas is bonded to the tar in the water and removed. The cooling caused by the quenching wash is responsible for the condensation of the tars contained in the gas and they too are removed. The washing process also removes all traces of alkali and chlorine which would be detrimental to a turbine. After this washing process the gas is ready for the gas turbine and has increased in volume fifty percent due to saturation by steam.

Although the gas is ready for the turbine the sulphur content must be lowered by a considerable margin before it can be released to the atmosphere. Ninety-five percent of the sulphur content of the gas is hydrogen sulfide, which can be removed by washing the gas with an ammoniacal liquor according to the following reaction:

$$NH_3 + H_2O + H_2S = NH_4HS + H_2O$$

The sulphur recovered in this manner is not completely lost. It can act as a feed stream and be converted into salable sulphuric acid. When the sulphur is used to produce sulphuric acid the cost of meeting the emission standards by removing the sulphur is .336 mills/kwh.

The synthetic fuel gas is now fed to a pressure reduction turbine to reduce the gas pressure from 300 psig to 140 psig. The turbine is used to compress the air feed to the gasifier. The fuel gas is now fed to a combustor and the gas turbine. The gas is burned in the combustor with stoichiometric amounts of air. The boiler is placed between the combustor and the gas turbine to control the temperature of the gas fed to the turbine without using excess air.

The present Lurgi process consists of five discrete steps:

1. Pressure gasification-formation of the crude contaminated gas.
2. Shift conversion-adjustment of the H_2/CO ratio to facilitate subsequent methanation, hydrogenation of carbonization products, and desulfurization of naptha gas.
3. Rectisol gas purification-adsorption process with organic solvents (preferentially methanol) to remove all impurities.

4. Methane synthesis-conversion of clean components (essentially CO and H_2 of gas to methane.
5. Gas liquor treatment-removal of phenols and ammonia (this is a side stream).

All parts of the Lurgi process have been proved in operating plants except for methanation to the point of comparability with natural gas. Successful bench scale tests have been concluded and demonstration of the process is underway to produce a gas having 970 Btu/cu ft.

Overall efficiency of the process is about 68 to 70%, so the current gasifier with a capacity of about 500 million Btu input would produce about 350,000 cu ft/hr of gas. A 250-million cfd plant would require about 30 of the standard gasifier units, which are each about 12 ft in diameter. The equipment is now as big as it can be for convenient transport. If it were made much bigger, it would have to be site assembled.

At present the conversion of coal to gas by the Lurgi process is cheaper than the conversion of coal to the same number of BTU's of electricity.

Three major energy companies announced in October 1972 that they were starting immediately on technical and economic feasibility studies for the construction of a gasification plant in northwest New Mexico. They are Texas Eastern Transmission Corp., Utah International Inc., and Pacific Lighting Corp. According to the announcement, they hope to begin operating one 250-million cfd plant in 1975 and the possibility of adding three additional plants in the future is being considered.

If the project proves feasible, Texas Eastern and Pacific Lighting will build and operate the plant, and they will contract with Utah International for the coal.

It is estimated that each 250-million cfd plant would consume 7.5 million tons of coal a year.

El Paso Natural Gas Company was the first firm to announce definite plans to build a 250-million cfd gasification plant. It applied to the FPC in November, 1972 for approval to build facilities based on the Lurgi process with methanation added. Initial plans called for startup in 1976 with full production attained in 1977. The gas is expected to have a heating value of 950 Btu/cu ft. Gas that El Paso currently delivers to California has an average heating value of 1070 Btu/cu ft.

The plant would be located in northwest New Mexico and would consume about 8.8 million tons of subbituminous coal per year. El Paso Gas and Consolidation Coal Company jointly hold a coal lease on 40,000 acres of land on the Navajo Indian Reservation. It is estimated that the land contains over 600 million tons of recoverable coal under less than 150 feet of over-burden. Therefore, conventional surface mining methods can be used.

HYGAS

In the HYGAS process, coal is first crushed, dried, and sized, and then sent to the pretreatment section. Here, agglomerating coals such as Eastern bituminous coals undergo a mild surface oxidation with air at about 800 ^{o}F. to prevent agglomeration in the hydrogasifier. Research is being directed toward eliminating this process step. Nonagglomerating coals, such as lignite and subbituminous, do not require pretreatment. The feed coal is slurried with a light oil (a byproduct of the process), pumped to hydrogasifier pressure (1,000 pounds per square inch gage), and fed to the top of the 135-foot hydrogasifier (reactor) vessel. In the upper section of the hydrogasifier, the slurry oil is evaporated. The vaporized oil leaves the vessel with the product gas from which it is then separated and later recovered for recycle. The coal falls by gravity through the reactor, passing first through a low-temperature (1,200° to 1,400 °F.) gasification zone where methane is primarily generated from the volatile matter in the coal. The devolatilized coal next passes into the lower section of the reactor. Here, the coal is hydrogasified at 1,700° to 1,800 °F. to methane by reaction with hydrogen and steam. This methane joins with the methane generated in the upper section to exit from the top of the hydrogasifier as the main constituent of the product gas. The product gas also contains hydrogen, steam, carbon dioxide, and carbon monoxide, along with hydrogen sulfide and other impurities.

To make this gas suitable for injection into the pipeline system, the gas must first be purified. It is scrubbed to remove carbon dioxide and sulphur-bearing gases. (The sulphur-bearing gases are further processed to produce elemental sulphur, a byproduct of the process.) The purified gas passes into a catalytic methanation section. Here, the carbon monoxide and hydrogen react in the presence of a catalyst at a pressure of 1,000 pounds per square inch and at temperatures ranging from 550° to 850 °F to form additional methane. The product gas, which is predominantly methane, is subsequently dried to remove the steam formed in methanation to produce the final produce-methane. At 1,000 pounds per square inch gage pressure, it is suitable for injection into a natural gas pipeline.

The reacted coal, now called char, is discharged from the bottom of the hydrogasifier. Approximately half of the initial coal fed to the hydrogasifier is gasified to methane. The remaining char contains significant amounts of unreacted carbon and can be used in any of several processes to generate the hydrogen-rich gas necessary in the HYGAS process.

The HYGAS pilot plant in Chicago for conversion of coal to pipeline quality gas has been made operational. The plant, together with supportive equipment, represents a capital investment of about $10 million. It is designed to convert 75 tons of coal per day to 1.5 million cubic feet of high-Btu gas.

Pilot plant construction began in 1969 and was completed in 1971. As of the fourth quarter of 1972, several significant operating runs have been made; the most notable being successful operation at 1,000 pounds per square inch gage. This is the pressure at which both the heat-generating methane-forming reactions and the heat-absorbing steam-carbon reactions occur at significant rates and is the pressure upon which the commercial plant design is based. Concentration of methane in the hydrogasifier effluent exceeded 40 percent. This corresponds closely to the design concentration. Operating problems, with essentially off-the-shelf mechanical equipment which delayed initial gas production, continue to be troublesome and require frequent shutting down of the hydrogasifier. The repeated heatup and shutdown has caused refractory spallins in the reactor and plugging of transfer lines. Unexpected severe expansion and concentration of high temperature internal piping has also been a problem. These conditions are being solved one at a time and semicontinuous operation of the hydrogasifier has been achieved. The gas purification and methanation systems have been checked out and are on standby awaiting continuous operation of the hydrogasifier[1].

Construction of the electrothermal gasification section was completed in June 1972. It has been pressure tested to 1800 psig and the electrical control system has been tested extensively. Operation of the HYGAS section of the plant with the package hydrogen plant is expected to be completed this spring and operation with the electrothermal gasifier can begin then.

Development work is also continuing on steam-oxygen gasification of coal char. The novel feature of this development is the gasification of char under nonslagging conditions in a high-pressure fluidized bed. Estimated construction cost for this section is about $2.5 million. Construction is projected to be completed by mid-1974, by which time testing with the HYGAS-electrothermal gasifier combination should be completed. Integration of the steam-oxygen gasifier will then be made with the HYGAS reactor for subsequent tests.

CO_2 Acceptor Process

Another process for which a demonstration plant has been constructed is the CO_2 Acceptor Process, developed by Consolidation Coal Company. Total funds for construction of the plant (over $9 million) were furnished by OCR. It will take an estimated $5 million per year to operate the plant. The plant is designed to use 1.5 tons per day of lignite and 3 tons of dolomite to produce 2 million scfd of 375-Btu/scf gas.

It is estimated that a commerical lignite gasification plant using the CO_2 Acceptor Process would cost about $150 million, use 30,000 tons of lignite per day, and produce 250 million scfd of pipeline gas. Present estimates indicate the gas would be in the $1/Mcf price range. Start of construction of the first commercial plant is projected for sometime in the 1974-76 period.

The unique feature of the CO_2 Acceptor Coal-Gasification Process is the circulation of calcined dolomite through a fluidized bed of lignite char operating under gasification conditions. The reaction of dolomite with carbon dioxide, one of the gasification reaction products, liberates heat sufficient to sustain the endothermic carbon-steam reaction, and also results in a product gas enriched in methane, and particularly enriched in hydrogen. Spent dolomite from the gasification zone is calcined in a separate regenerator using air and high-ash char from gasification as a source of fuel, thus eliminating the need for an expensive oxygen plant.

The development of this concept by Consolidation Coal Company had been carried through the laboratory stage by 1964 when the Office of Coal Research awarded a contract to complete the bench-scale development of the process. This phase was completed successfully in 1968. Feasibility studies before and after the bench-scale work indicated the process had potential commercial possibilities.

The conceptual design of a pilot plant was completed in April 1967. Design of the pilot plant was based upon extrapolation of bench-scale data obtained in the 1964 to 1968 period. The pilot plant is designed to operate at pressures of 150 to 300 per square inch gage and temperatures up to 1,800 ^{O}F. Proper operation requires carefully controlled flows of char and dolomite, as well as fluidizing gases, to the several fluidized vessels under balanced pressure conditions.

Construction of the $9 million pilot plant at Rapid City, South Dakota, was initiated in January 1970, and completed in November 1971.

At the completion of the plant shakedown tests in April 1972, a series of startup attempts was initiated. Each run was terminated due to some mechanical problems which have since been solved.

BI-GAS

The BI-GAS process employs an entrained bed, rather than a fixed or fluidized bed, and all types of coal may be used in the gasifier without pretreatment. The two-stage gasifier is said to be relatively simple in design and subject to scale-up to very large installations. Work has been carried out on a laboratory scale with a 100-lb/hr reactor. General objective of this test program was to optimize the controlling operating variables of temperature, pressure and residence time, for maximum methane formation in Stage 2 of the gasifier. The program reportedly confirmed the original concept that methane could be produced in high yield directly from coal in an entrained gasifier.

Present methanation processes are based on fixed-bed catalytic reactors. In connection with the BI-GAS program, work is directed toward development of a methanation system based on a fluidized-bed catalytic reactor. Design details for a nominal 6000 scfh fluidized-bed unit have been completed and equipment erected. Data from this unit will be used for the design of the pilot plant methanator.

The heat of the BI-GAS process is the two-stage gasifier which uses pulverized coal (70 percent minus 200 mesh) in entrained flow. Fresh coal and steam are introduced into the upper section (stage 2) of the gasifier at pressures in the range of 70 to 100 atmospheres. In stage 2, the coal comes in contact with a rising stream of hot synthesis gas produced in the lower section (stage 1) and is partially converted into methane and more synthesis gas. The residual char entrained in raw product gas is swept upward and out of the gasifier. The char is separated from the product gas stream and recycled to stage 1 of the gasifier.

In stage 1, the char is completely gasified under slagging conditions with oxygen and steam, producing both the synthesis gas and the heat required in stage 1 for the partial gasification of the fresh coal.

The raw product gas from stage 2 is purified by removal of hydrogen sulfide and carbon dioxide and upgraded in Btu content to pipeline quality by catalytic methanation.

The BI-GAS process offers several advantages in the production of synthetic natural gas:

1. A high yield of methane is obtained directly from coal, and subsequent processing of the product gas is minimized.

2. Because it is entrained rather than a fixed or fluidized-bed system, all types of coal should be amenable without prior treatment for use in this gasifier.

3. The conditions in stage 2 are such that no tar and oils are formed in the gasification process.

4. All the feed coal is consumed in the process; principal byproducts are slag for disposal and sulphur for sale.

ATGAS

The ATGAS process uses molten iron to gasify all types of coal with steam and oxygen at low pressure for the production of a gas suitable for conversion to synthetic natural gas. The ATGAS process eliminates the problem of feeding coal into high pressure gasifiers. Any type and size of coal can be used for synthetic natural gas production.

The gasifier is a cylindrical refractory-lined vessel (Figure 20) containing molten iron with a slag layer floating on the iron. Coal and limestone are injected through tubes (lances) placed relatively deep in the molten iron, using steam as the carrier. The coal devolatilizes with some thermal cracking of the volatiles leaving the fixed carbon and sulphur to dissolve in the iron. The dissolved carbon is oxidized to carbon monoxide with oxygen that is introduced via lances shallowly immersed in the iron bath. The dissolved sulphur (both organic

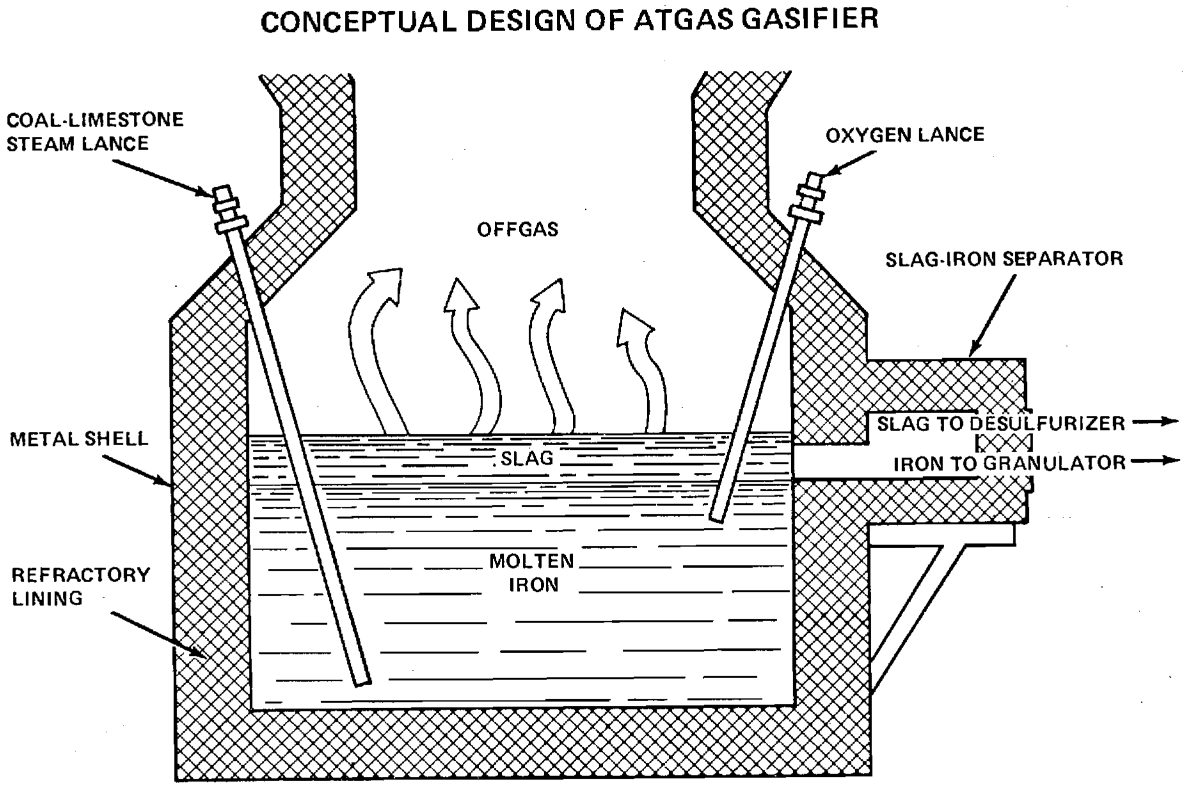

Figure 20. Conceptual Design of ATGAS Gasifier

and pyritic) migrates from the molten iron to the slag layer where it reacts with the lime to produce calcium sulfide. Provided the carbon content of the molten iron is maintained relatively high (3 to 4 percent), the injected oxygen and steam preferentially react with carbon without sulphur oxidation to form hydrogen and carbon monoxide. Thus, the oxidation of fixed carbon, the cracking of volatile matter, and dissociation of water (introduced via the reactor with the coal) produce a hot (2,600 ^{o}F) off gas consisting mainly of carbon monoxide, hydrogen, and possibly methane.

Capital investment for a 250 MMscfd ATGAS plant is eatimated to be about $200 million. With 12,600 Btu/lb coal at 30¢/million Btu, the estimated 20-year average price of gas is $1.10/million Btu. With the same coal available at 20¢/ million Btu, the average price would be 95¢/million Btu.

Self-Agglomerating Gasification Process

This process is a two-stage fluidized-bed system for steam gasification of coal. The heat requirement for the endothermic gasification reaction is developed by fluidized-bed combustion of a part of the carbon bed. Air is used for combustion. The heat for the gasification reaction is provided by recirculation of coal ash from the burner through a fluidized-bed gasifier.

A major feature of the process is the method of combustion which applies the "self-agglomerating" fluidized-bed technique for burning coal with simultaneous pelletization of the ash during the combustion. The ash agglomerates formed in the combustion bed are free-flowing spherical particles. These are circulated through the gasifier as a direct-contact heat-transfer medium to provide the heat for the steam-carbon reaction. This pelletized ash, after giving up a part of its sensible heat in the gasifier, is returned to the burner to moderate the burner temperature and be reheated for return to the gasifier.

In addition to providing a pelletized heat-transfer medium to the gasifier, the self-agglomerating fluidized-bed burner is effective for collecting the ash contained in the incoming fuel. Thus, the fuel can be burned to yield a combustion gas essentially free of flyash. This particulate-free hot combustion gas can then be expanded in an open-cycle gas turbine for recovery of kinetic energy.

Koppers-Totzek Process

In the K-T process (Figure 21), coal is reacted with steam and oxygen in a patented gasifier to form a raw synthesis gas. The gas is cooled and all particulate matter is removed. Upgrading to natural gas quality would involve chemically removing the acid gases produced and then shift conversion and methanation steps. Because of the high temperature reaction in the gasifier (about 2700 F),

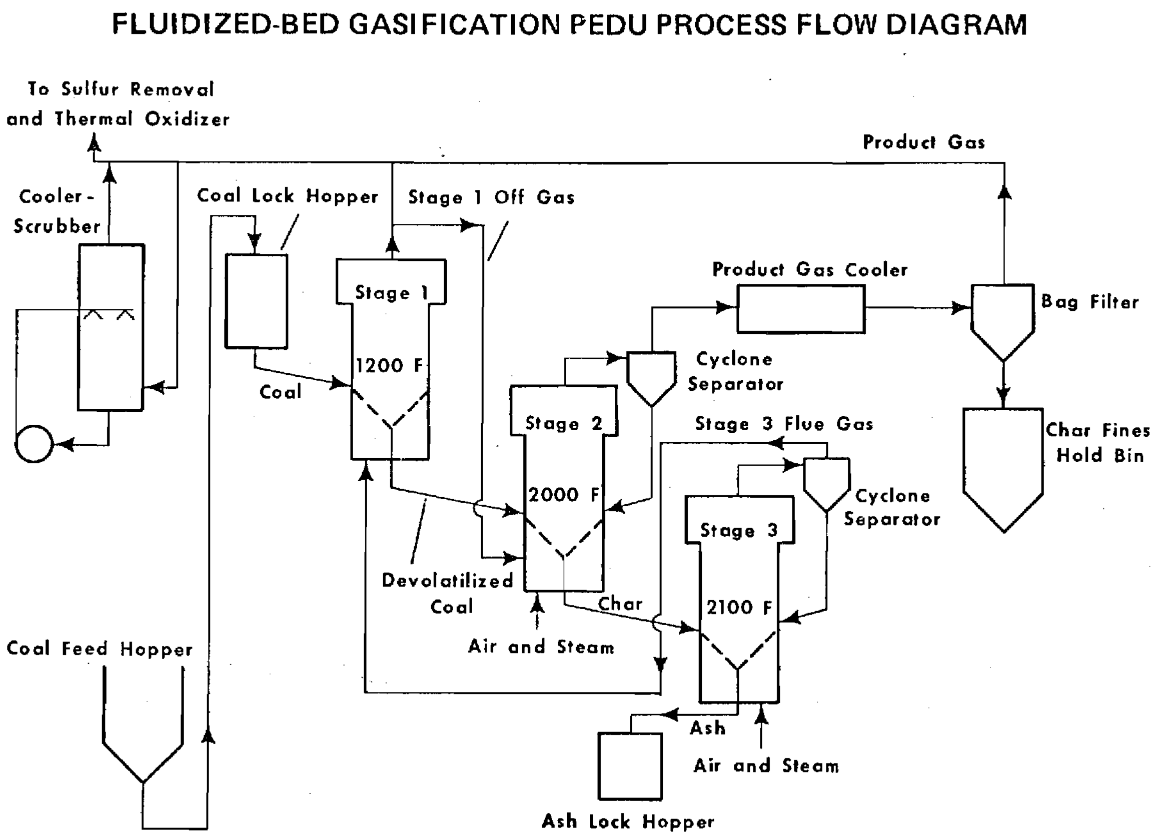

Figure 21. Koppers-Totzek Process

it is claimed that the raw gas produced by the K-T process is free of condensable organic compounds. Therefore, potential gaseous or liquid pollutants such as ammonia or phenotic effluents are not produced.

Koppers Company designed and built the first demonstration unit for gasifying coal in suspension based on the K-T process in 1948 for the U. S. Bureau of Mines in Missouri to demonstrate the feasibility of using the process to produce gas for conversion to synthetic liquid fuels. It was operated jointly by the Bureau and Koppers Company with the assistance of Heinrich Koppers engineers. Production at the plant was discontinued in 1950 after a successful demonstration period.

The design of a process and equipment development unit (PEDU) for studying fluidized-bed catalytic methanation was completed in 1971 under subcontract with

Koppers Company, Inc. The 6,000-cubic-foot-per-hour PEDU was scheduled to be operational early in 1973.

The Slurry Methanation Process

In this process an inert liquid is pumped upward through the reactor at a velocity sufficient to fluidize the material and remove the reaction heat. The low BTU feed gas is also passed upward through the reactor so it is converted to a high concentration methane stream. This process is illustrated in Figure 22.

SLURRY METHANATION EXPLORATORY UNIT

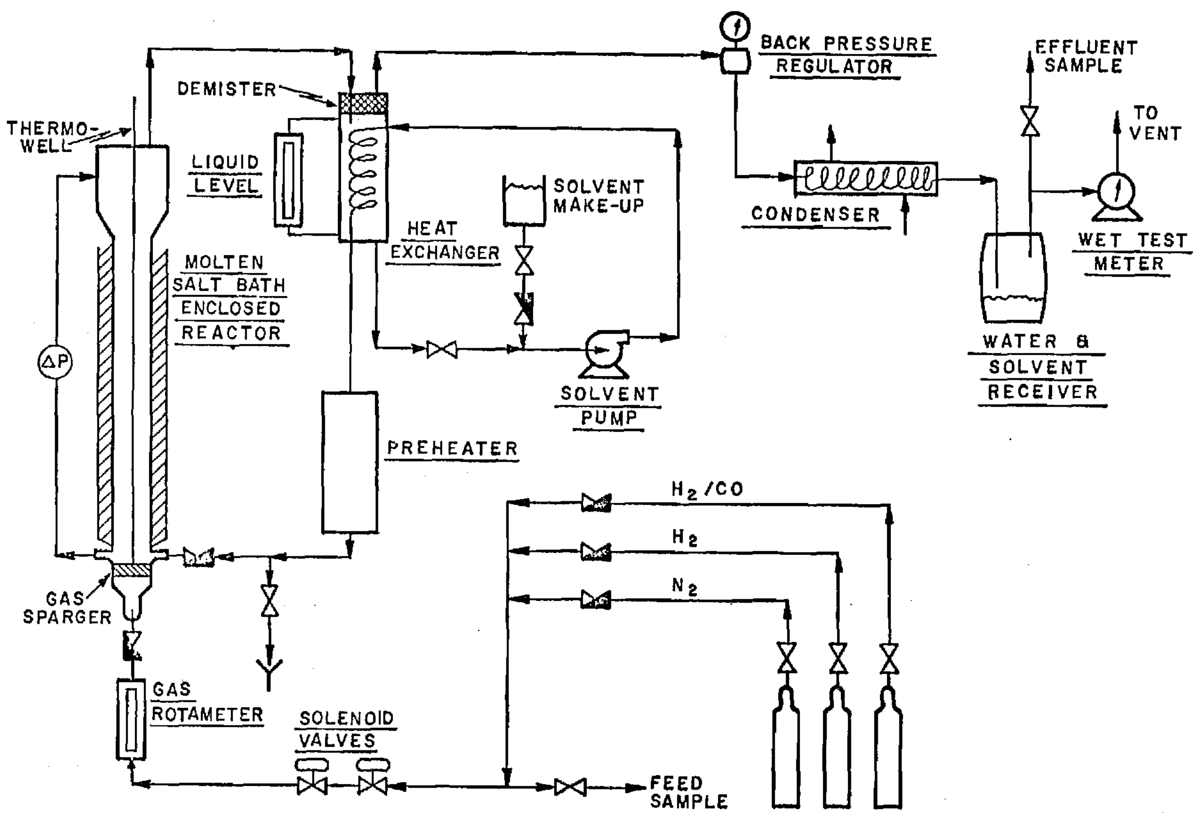

Figure 22. Slurry Methanation Process

Electrofluid Coal Processing

In the electrofluid reactor, coal char is heated by passage of an electric current through a fluidized bed of conducting char particles. A process for production of synthesis gas from coal char and steam has been demonstrated in bench-scale reactors. Moreover, the Institute of Gas Technology has adopted this method to generate synthesis gas for the HYGAS pilot plant in Chicago, Ill., and the method may be incorporated in future large-scale commercial plants for manufacturing methane.

The gasification process was demonstrated by employing a 12-inch diameter electrofluid-bed reactor which was operated both batchwise and with continuous feeding of coal char. Reasonably adequate steam conversions and gasification rates were obtained while operating at atmospheric pressure and temperature in the range of 1,400° to 1,900 °F. The operation was generally smooth with no serious difficulty encountered in controlling electrical power. However, it became evident that the electrodes in contact with the fluidized bed could become overheated which tended to shorten electrode life. Moreover, a preliminary study of the electrical characteristics of fluidized-bed systems showed that these characteristics were complex and that engineering methods for measuring, analyzing, and predicting them needed to be developed in order to properly design industrial-scale reactors. (Figure 23).

The 12-inch diameter reactor was modified and operated to further evaluate the coal char gasification process. The modification included changes in the electrode system and power supply so the reactor could be operated on three-phase power. These changes enabled operation with higher power inputs. Electrodes made of silicon carbide were tested extensively and found to be quite durable.

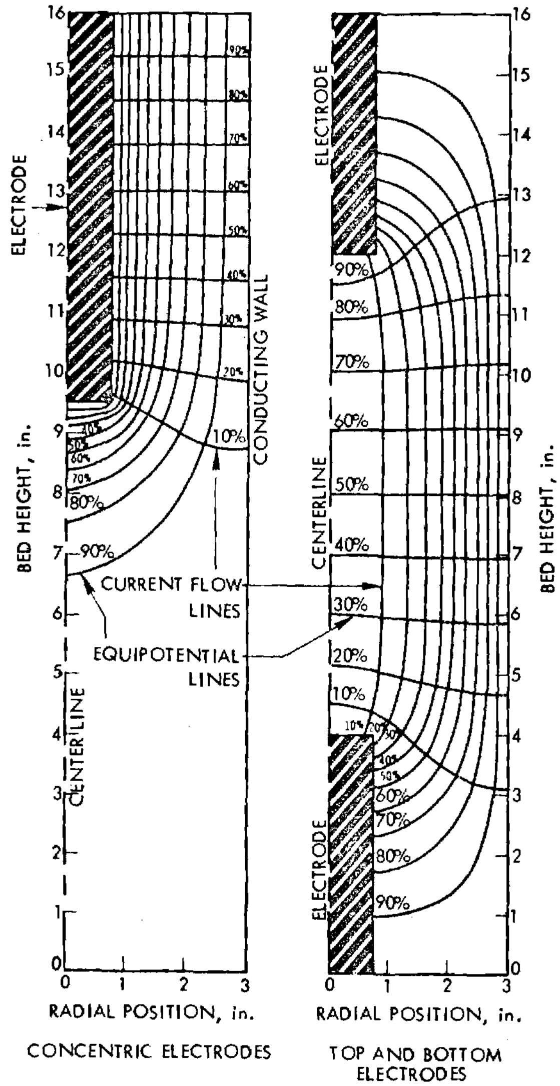

Figure 23. Current Distributions in Electrofluid Coal Gasifiers

However, under some conditions the electrodes became heavily coated with ash or slag. The extent of coating appeared to be related to the char source. The electrical characteristics of fluidized-bed systems were also investigated extensively. The resistivity of fluidized beds was measured under a wide variety of conditions including temperatures varying from ambient to 1,500 ^{o}F. Arcing or sparking in fluidized beds as well as electrode-to-bed contact resistance received attention. At the same time, extensive use of field theory was made to predict and analyze the electrical characteristics of fluidized beds. A preliminary demonstration of the feasibility of a process for producing carbon disulfide by reacting sulphur and coal char in an electrofluid reactor was also completed. The demonstration included operating the electrofluid-reaction system over a range of temperatures and sulphur feed rates.

NEW TECHNOLOGIES

Fluid-Bed Boilers

Fluidized beds have two major attributes arising from the rapid agitation of the relatively dense particle phase: (1) rapid heat and mass transfer occurs between the gas and the particles, and (2) high heat transfer coefficients are obtained at surfaces immersed within the bed in comparison with gas-to-surface heat exchange.

Early research work into fluidized combustion utilized only the high heat and mass transfer between the phases in attempts to burn fuels intractable to conventional methods, e.g.anthracite fines, lignite, oil shale, and washery tailings. Much of this work was successful, resulting in at least one commerical system. However, the approach to heat utilization was conventional in that the aim was to heat the combustion gases to the maximum obtainable temperature and pass them through conventional water-tube boiler systems. For fuels with an ash content less than about 70 percent, combustion in the fluidized bed was so rapid that the combustion temperature was higher than the melting point of the ash.

With heat extracted directly from tubes in the bed, very high heat release rates could be obtained, resulting in a more compact boiler (compared with conventional plant) and a consequent reduction in capital cost. It also seemed likely that operating costs would be reduced by the use of low-grade fuels and that the relatively low combustion temperatures would alleviate deposit and corrosion troubles.

In the boiler shown in Figure 24, coal was pneumatically fed to the center of the bed just above the air distributor, and the flue gases passed through a heat exchanger to a cyclone. The particles from the cyclone could be passed to waste or recycled to the combustor in any required proportion. The combustor was water cooled.

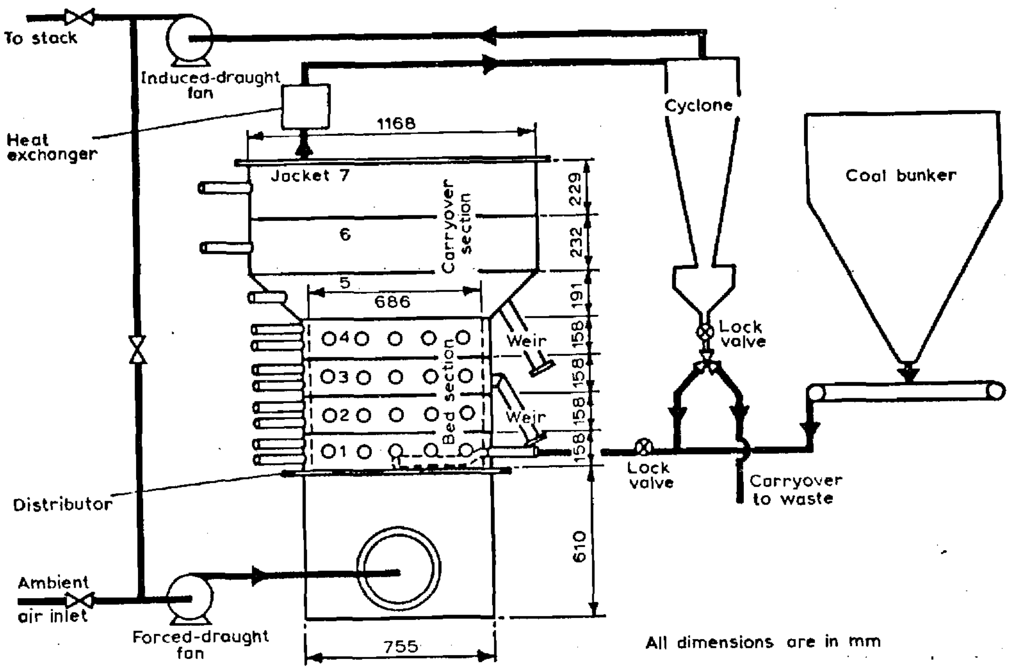

Figure 24. Fluidized-Bed Boiler

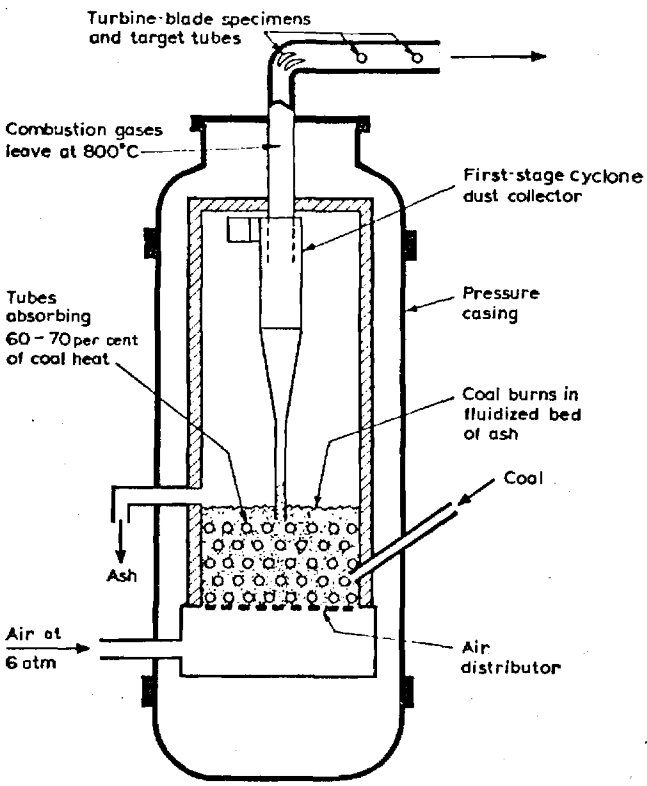

Figure 25. 4 Ft. x 2 Ft. Fluidized Bed Combustor

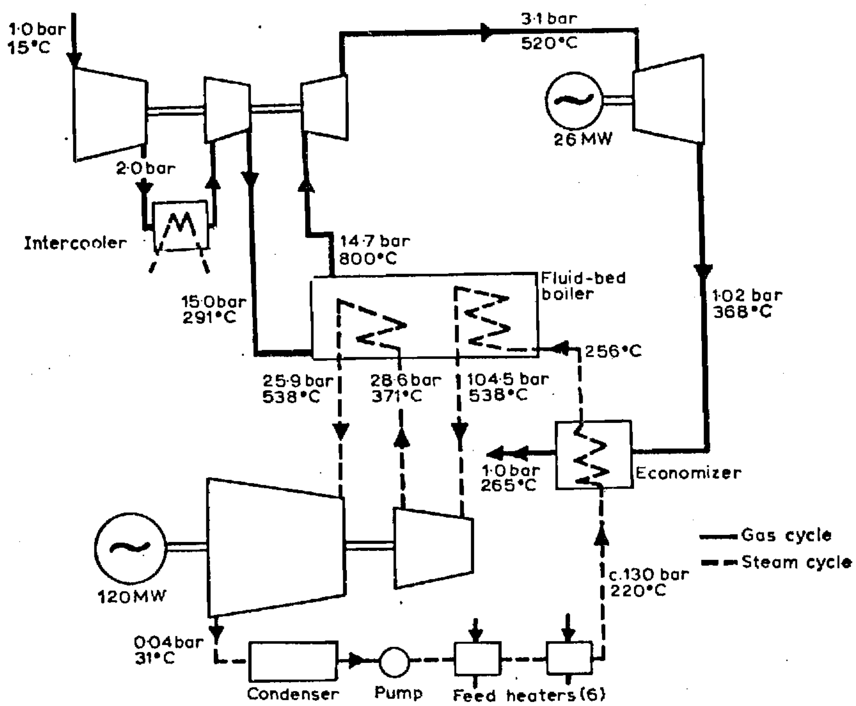

Figure 26. Combined Cycle Power Plant

Figure 25 illustrates a small fluidized bed boiler, and Figure 26 a 140 MW_e combined cycle power plant using a fluidized bed boiler.

MHD

Magnetohydrodynamics has great potential for supplying electricity at higher efficiencies than at present, and with minimum environmental impact. While the principle has been demonstrated often in short-time experiments of relatively small scale, a great deal of work remains to be done before the availability of long-lived coal-fired central-station MHD generating units becomes a reality.

Fuel is burned at a pressure of 6 or 7 atmospheres, and the resulting hot gas then flows at a high velocity through a duct within a magnetic field. The gas must be at such a high temperature that it is electrically conductive. (This conductivity may be enhanced by potassium or cesium seed.) When a conductor cuts a magnetic field an electric current is generated-as in the ordinary rotating turbine-driven generator. Electrodes on the sides of the duct collect the current.

This constitutes a thermal-electric generator with no moving mechanical parts. The gas from the MHD duct, still very hot, may flow to a conventional steam boiler to power a standard steam turbogenerator. The first generation of such plants is expected to reach a thermal efficiency of around 50 percent. Eventually 60 percent is believed attainable.

Aside from the need for better understanding of the dynamics within the MHD duct, the problems are largely associated with the very high temperatures which require the development of new materials and methods of construction for dependable performance over a period of years. There are additional problems associated with seed recovery, coal ash and slag, and large superconducting magnets. Nonetheless, rational solutions are envisioned.

AIR POLLUTION

Health Effects

The most obvious adverse environmental effect of energy generation to date has been the air pollution which is evident in most major cities of the world. This air pollution is almost entirely due to the combustion of fossil fuels, and results in damage to people, to property, and to plant and animal life. Table 10 lists the five major pollutants and their sources.

Table 10. Sources of Air Pollution (millions of tons per year)

Source	CO	SO_x	NO_x	Hydro-carbons	Particu-lates	Total	%
Transportation	66	1	6	12	1	86	60
Industry	2	9	2	4	6	25	17
Electric Power	1	12	3	1	3	20	14
Heating	2	3	1	1	1	8	6
Waste Disposal	1	1	1	1	1	4	3
TOTAL	72	25	12	18	12	143	100

As can be seen, even though electric power plants burn about 25% of fossil fuels, they only contribute 14% of the air pollution. Internal combustion engines, with their low efficiency, release 2/3 of the unburned hydrocarbons, practically all of the carbon monoxide, and 60% of all air pollution. Internal combustion vehicles and industry are also concentrated in areas of high population density, whereas power plants tend to be located on the outskirts of these areas. Thus, the automobile is the worst polluter. Cleaning up automobile emissions alone should tremendously reduce air pollution in the large cities. Space heating consumes as much energy as transportation but produces very little air pollution because most space heating is done with gas, the cleanest of the fossil fuels. In some areas, electric power companies are being required by law to burn gas or oil instead of coal in order to meet emission standards. Table 11 presents emission rates for the five major pollutants from a fossil fueled power plant assuming no pollution control equipment, other than flyash control when coal is burned. Electrostatic precipitation can remove practically all of the particles from the exhaust. The gaseous pollutants are difficult to remove.

Table 11. Annual Release from a 100 MW_e Power Plant (millions of pounds)

	Coal	Oil	Gas
CO	1.15	0.018	---
NO_x	46	48	27
SO_x	306	116	0.027
Hydrocarbons	0.46	1.47	---
Particulates	10	1.6	1.02

Perhaps the most serious single air pollution incident was the London smog in the winter of 1952-1953 in which 4000 people died. At that time the primary fuel for space heating and industry was high sulphur coal. The high atmospheric concentration of sulphur oxides, which combine with fog droplets to form sulphuric acid, was responsible for most of these deaths. Since that time, the British government passed the Clean Air Act, and it is being enforced. This Act requires residents of London and other parts of Britain to burn only smokeless fuels in their homes and requires smoke from factory chimneys to be controlled. Since this act was passed, smog has practically disappeared from London.

When an electric utility shifts from high sulphur coal (2-3% sulphur) to low sulphur coal (1% or less) or other cleaner fuels, its fuel costs increase. For example, in 1967 when Consolidated Edison contracted for 1% sulphur coal to replace the 1.6% sulphur coal they had been using, their fuel costs increased from 33¢/Mbtu to 37¢/Mbtu, an annual cost increase of $7.5 million. This cost increase was, of course, passed on to the consumer through a rate increase. Burning low sulphur coal reduces the efficiency of electrostatic precipitators, so simply shifting to low sulphur coal in a plant results in a decrease in SO_2 emission and an increase in the release of particulates. New York City's regulations require that 99% of the particulates be collected. Some plants which had been operating with 99% collection efficiency released more particulates when the switch was made to low sulphur coal, so expensive additional equipment had to be installed to reduce particulate emissions to the previous level. Many utilities are required to burn low sulphur oil (1% or less), which is considerably more expensive than oil with a higher sulphur content and has a lower viscosity, resulting in equipment changes. The first commercial desulfurization plant for fuel oil is now operating in Venezuela and will furnish 100,000 barrels a day to the United States. This plant reduces the sulphur content from 2.6 to 0.5 percent. The requirement of low sulphur content has increased the prices of usable coal and oil to the extent that natural gas is economically competitive in some areas.

There is a synergistic effect with SO_2 and particulates, over 75% of which are from industry and power plants. In the presence of atmospheric particles which contain iron, manganese, or vanadium, SO_2 reacts to form sulfuric acid, a severe irritant to the bronchial system and lungs. This accounted for the large number of deaths from the London smog. SO_2 and particulates together are more damaging than either alone.

The dolomite process has recently been utilized by several power plants to reduce SO_2 emissions. Dolomite, a limestone, is injected into the combustion chamber as a powder where it reacts with about 20% of the SO_2 and practically all of the SO_3. The gas then flows to a wet scrubber containing an aqueous suspension of limestone or lime particles that removes more SO_2 as well as the fly ash. This system removes about 80% of the SO_2, essentially all of the SO_3, about 20% of the nitrous oxides, and 99% of the flyash. The resulting total solids collected is three times greater than the fly ash alone, so a solid waste disposal problem has been substituted for an air pollution problem.

Most hydrocarbons and oxides of nitrogen are released into the air of our cities by internal combustion vehicles. These hydrocarbons react with the nitrogen oxides in the presence of solar ultraviolet light to produce photochemical smog of the type that appears so often over Los Angeles and other cities. These reactions produce ozone and complex organic compounds which can have a serious effect on people, animal life, and vegetation. Ozone particularly is highly damaging to plant life. Photochemical smog is basically different from the type of smog formed from high SO_2 concentrations. Also, the automobile is the primary source of the pollutants which cause photochemical smog, whereas the sulfurous smog is the result primarily of factories and power plants. The effects of either type of pollution on people can be quite serious, especially for those with allergies or other respiratory conditions. New emission standards for automobiles to go into effect in 1975 should reduce emission of carbon monoxide and unburned hydrocarbons considerably.

Seven common respiratory diseases which have been associated with air pollution are cancer of the respiratory system, chronic bronchitis, acute bronchitis, the common cold, pneumonia, emphysema, and asthma. Ridker[14] calculated the total cost in the United States of these respiratory diseases in terms of 1958 dollars to be $2 billion. Quite a few studies have been carried out using the basic numbers provided by Ridker, apportioning a part of this respiratory disease cost to air pollution. The usual way of doing this is to compare the incidence of respiratory disease in urban and rural areas and attribute the difference in incidence to air pollution in the urban areas. The ratio of urban incidence to rural incidence is called the urban factor.

Lave and Seskin[15] provided a detailed analysis of studies up to that time which indicated a strong correlation between the urban factor and respiratory disease. In the case of air pollution and lung cancer they cited studies showing a ten-fold difference between death rates in rural and urban areas in England, and another study showing that the urban death rate due to lung cancer is twice as high as that in rural areas of England, and another study showing that the urban death rate due to lung cancer is twice as high as that in rural areas of England and Wales. Evidence for other parts of Europe also shows an association between lung cancer and the urban factor. Also cited are American studies which show that the death rate due to lung cancer is 34 per 100,000 in rural areas as compared to 56 per 100,000 in cities with population over 50,000. When standarized with respect to both smoking habits and age, this lung cancer rate is adjusted to 39 in rural areas as opposed to 52 in cities of over 50,000, which indicates that the urban factor is responsible for 25% of lung cancer in cities. Buell et al.[16] summarized lung cancer mortality studies to that time and showed that the ratio of the lung cancer rate in the city to that in rural areas ranged from 1.26 to 2.23, and was slightly higher when only non-smokers were considered. Also, studies of the mortality rate due to cardiovascular disease have shown that the mortality rate is 10% to 20% higher in urban areas as opposed to rural areas. These comparisons are typically made of matched groups with similar smoking habits. As a result of these and other studies, Lave and Seskin concluded that "there would be a 25 to 50% reduction in morbidity and mortality due to bronchitis if air pollution in the major urban areas was abated by about 50%," and that "about 25% of the mortality from lung cancer could also be saved by a 50% reduction in air pollution." These conclusions are based on the assumption that the urban factor is entirely due to air pollution in the case of respiratory disease, including lung cancer. Carrying this assumption one step further, they conclude that the urban factor would be eliminated by a 50% reduction in air pollution, since a 50% reduction in pollution would be expected to result in an air quality equal to that of the cleaner areas.

Using the correlation between urban and non-urban areas, and assuming the difference to be due to air pollution, over 20% of cardiovascular morbidity and about 20% of cardiovascular mortality could be eliminated if air pollution were reduced by 50%. Likewise, they estimated that 15% of non-respiratory cancer would be saved by a 50% reduction in air pollution.

The fallacy of these arguments, which are found throughout the literature describing health effects of air pollution, is the assumption that the urban factor is either due entirely to air pollution or is largely caused by air pollution. The basic assumption that is made, which seems reasonable until investigated further, is that the major causative factor for the difference in frequency of these diseases between urban and rural areas is the greater air pollution in the urban areas.

Goldsmith[17] analyzed data regarding respiratory disease, heart disease, and cancer and pointed out that there is a great deal of evidence favoring urban factors in the epidemiology of lung cancer and other respiratory disease, and that it appears to have a synergistic relationship to the well-established effect of cigarette smoking, but that "While many have considered that the factor might be air pollution, a number of consequences should follow which have not been observed: 1) the urban factor should be largest in those counties where there is the heaviest urban pollution; it is not, 2) assuming that the larger the city the greater the population exposure will be to air pollution, then the urban factor should increase regularly with city population; it does not, at least in the United States, 3) if exposure to urban pollution causes an augmentation in lung cancer, then the rates should be higher in lifetime urban residents than in migrants to urban areas; they are not, 4) correlations of lung cancer rate with major pollution should be found by studies in the United

Kingdom where lung cancer rates are high and pollution is great; a positive correlation is found with population density and not with pollution, 5) if the urban factor were community air pollution, it should affect women at least as much as men; it does not." Goldsmith continued, "There may be other explanations of the urban factor (greater smoking, occupational exposure, population density, infections), but the evidence presently available that it is air pollution does not confirm the suspicion of casualty which previously existed." Williamson[18] also discussed the urban factor and stated that "We emphasize that a casual relationship between air pollution and this factor has been neither established nor refuted. However, there is a strong possibility air pollution is at least a contributory cause." Obviously, air pollution does enhance respiratory disease, but the question which one must answer in order to arrive at realistic projections of health costs of air pollution is how much of respiratory disease is caused by air pollution. Lave and Seskin may have grossly overestimated the costs due to air pollution by attributing the urban factor solely to air pollution and assuming also that the urban factor could be eliminated by a 50% reduction in air pollution.

The Surgeon General's report on Smoking and Health[19] make it quite clear that cigarette smoking is the major cause of respiratory disease in the United States. Drastic increases over the last few decades in the incidence of respiratory disease and lung cancer are correlated with the rapid increase in cigarette smoking. As stated in the report, "Cigarette consumption in the United States has increased markedly since the turn of the century, when per capita consumption per person was 138. It rose to 1,365 in 1930, to 1,828 in 1940, to 3,332 in 1950, and to a peak of 3,986 in 1961. Similarly, lung cancer deaths, less than

3,000 in 1930, increased to 18,000 in 1950. In the short period since 1955, deaths from lung cancer rose from less than 27,000 to the 1962 total of 41,000. This extraordinary rise was not recorded for cancer at any other site. Deaths from heart disease also rose from 273,000 in 1940 to 578,000 in 1962. It is also shown that, in comparison with non-smokers, average male smokers of cigarettes have a ten-fold risk of developing lung cancer and heavy smokers at least a twenty-fold risk. Cigarette smoking is the most important of the causes of chronic bronchitis and emphysema." It is further stated that "for the bulk of the population in the United States, the relative importance of cigarette smoking as a cause of broncho-pulmonary disease is much greater than atmospheric pollution or occupational exposure." A recent report by the Environmental Protection Agency states that smoking causes three times as much respiratory disease as air pollution.[20]

In this paper actual data on incidence of respiratory disease are used in the analysis, which is physically reasonable and which properly accounts for the relative effects of smoking and air pollution. From the results of this analysis the following conclusions may be drawn regarding air pollution related respiratory disease: 1) the major cause of respiratory disease in the United States is cigarette smoking, and 2) although the incidence of these diseases in urban areas is greater than in rural areas, it has not been shown that this urban factor is primarily due to air pollution. There is evidence that air pollution is a contributor to the urban factor, but it is not the only contributor, and possibly not even the major contributor. Much of respiratory disease is communicable, and in urban areas the higher population density facilitates its transmission. Other infectious diseases (possibly including some forms of cancer) are more easily transmitted in the urban areas because of the higher population densities. Because of more crowded urban conditions, urban non-smokers also inhale more tobacco smoke produced by tobacco smokers than is the case for rural non-smokers. Also, significant differences exist between rural and urban areas with respect to life styles, diet, and other factors which can strongly affect the health of an individual. Another factor which could be a major contributor to the urban factor for death rates due to major illnesses is the fact that many rural people tend to go to a nearby major city to be treated for major illness. Since demographic data records deaths only by place of occurrence, if a rural person dies while hospitalized in a nearby city, this would show up in the urban death rate. Unless a detailed study is made to determine death rates by place of residence, this factor could have a big effect.

Bates[21] concluded that 70% of respiratory disease is due to cigarette smoking. This is in general agreement with the Surgeon General's report on Smoking and Health[19]. Thus, the percentage of respiratory disease due to cigarette smoking is taken to be 70%. Of the remaining 30% of respiratory disease, the urban factor accounts for 50% of the respiratory disease in cities, keeping in mind that studies of the urban factor compared groups of equal smoking habits in order to eliminate the effect of smoking.

Results cited by Goldsmith and others indicate that air pollution is not the major cause of the urban factor, since there is a stronger correlation between the urban factor and population density than there is between the urban factor and air pollution levels. Many factors help account for the difference in incidence between urban and rural areas, and air pollution is certainly one of these factors. In a few cases, such as Los Angeles, air pollution may in fact be the major cause of the urban factor; but in most cities, it is not. In arriving at total costs of respiratory disease due to air pollution, one must assign a portion of the urban factor (averaged over all metropolitan areas) to air pollution. It is the considered opinion of the authors that, in view of the many studies which have so far been reported, air pollution does not account for more than 50% of the urban factor. If the contribution were greater than 50%, strong correlations with air pollution levels would have been cited by Goldsmith[17] and Williamson[18], instead of the lack of correlation which they reported. On the other hand, the authors agree with Williamson in that "there is a strong possibility that air pollution is at least a contributory cause." Thus, we assign a minimum contribution of 10% of the urban factor to air pollution.

The effects of cigarette smoking and the urban factor are synergistic, not additive. Some previous cost studies make the mistake of assuming that these effects are additive and assign costs independently to the urban factor and cigarette smoking.

With regard to non-respiratory disease, there have been studies which show some correlation with the urban factor and smoking. But even though a slight correlation between the urban factor and non-respiratory diseases, such as cancer, has been shown to be valid, there is no justification at present for assuming that this correlation is due to air pollution. There are too many other factors which may be more important. Likewise, it has not yet been conclusively proven that smoking is a significant cause of non-respiratory disease.

The health cost of air pollution is calculated to be between \$62 million and \$311 million[22]. This is lower than some of ten-cited estimates of total health cost due to air pollution because most estimates don't separate out the effect of cigarette smoking, and they also start with the assumption that the urban factor is either totally or primarily due to air pollution. As has been pointed out clearly by Goldsmith and others, the urban factor is probably not primarily due to air pollution for a variety of reasons. It is probably more connected with factors such as: population density effects on transmission of infectious diseases, significant differences in life styles between urban and rural areas, urban non-smokers being affected more (because of higher population density) by inhalation of cigarette smoke produced by smokers, and rural persons dying after coming to a nearby city for hospitalization (thus contributing erroneously to the demographic data on urban death rate). Factors such as these may be major contributors to the so-called urban factor.

Lave and Seskin[15] calculated the total health cost of air pollution in 1963 to be $2.08 billion. They assumed that "25 percent of all morbidity and mortality due to respiratory disease could be saved by a 50 percent abatement in air pollution levels. Since the annual cost of respiratory disease is $4887 million, the amount saved by a 50 percent reduction in air pollution in major urban areas would be $1222 million." They also assumed that a 50 percent reduction in air pollution would reduce cardiovascular disease by 10 percent and reduce cancer by 15 percent, saving $468 million and $390 million, respectively. Thus, they arrived at a total 1963 cost of $2.08 billion which would be saved if air pollution were reduced 50 percent, resulting in an air quality equal to that of relatively non-polluted areas to which the polluted areas had been compared. In these estimates, half or more of the urban factor was attributed to air pollution, both for respiratory and non-respiratory disease.

Barrett and Waddell[23] further inflated the Lave and Seskin estimate by assuming that if a 50% reduction in air pollution would result in a savings of

\$4.16 billion. They arrived at a 1968 cost by multiplying the \$4.16 billion by the fractional increase in Gross National Product from 1963 to 1968, for a total health cost of \$6.06 billion. One difficulty with this estimate is that the data on which Lave and Seskin based their estimates of \$2.08 billion more properly represented a cost due to all air pollution, rather than costs due to half of the air pollution. Lave and Seskin spoke in terms of a 50% reduction in air pollution since that is what would be required to improve the air quality to that of relatively non-polluted areas, where air pollution was not believed to be a significant health factor.

The RECAT Committee took the inflated Barrett and Waddell estimate of \$6.06 billion to be a cost due to SO_2 and particulates alone, and by employing the Caretto-Sawyer emission severity factors, used it to project a total 1968 health cost of \$15.168 billion for all pollutants. Their reasoning was that since the air pollution index used by Lave and Seskin incorporated only SO_2 and particulate measurements, then the observed effects costing \$6.06 billion were due to SO_2 and particulates alone. This would be true if there were no correlation between SO_2 and particulate pollution and other types of air pollution, but in fact they usually do correlate strongly. During episodes and general adverse weather conditions, all pollutants usually show high concentrations, and in roughly the same areas. Thus, even though the numerous studies cited by Lave and Seskin often used only smoke or smoke and sulfation as an air pollution index, the effects which they report are usually effects due to all air pollution, not SO_2 and particulates alone. In fact, most of these correlations are actually with the urban factor (comparing "clean" rural areas with "dirty" urban areas) which may have little relation to air pollution. As stated by Barrett and Waddell, "Lave and Seskin seem to have a stronger faith in the magnitude, sign and statistical significance of their regression coefficients than what their analysis would seem to support. Their many statements about the causes of these 'effects' are not as justified as they seem to conclude." Lave and Seskin clearly intended their cost estimate of $2.08 billion to represent a cost of air pollution in general, not just SO_2 and particulates.

What has happened in arriving at the $15.168 billion health cost due to air pollution is that a rough estimate of $2.08 billion has been inflated twice using highly questionable techniques. The Lave and Seskin estimate of $2.08 billion for all air pollution was inflated by Barrett and Waddell to $6.06 billion for all air pollution; then the RECAT Committee took the $6.06 billion value to be only due to SO_2 and particulates, so proportional costs were assigned to CO ($303 million), hydrocarbons ($6.06 billion), and NO_x ($2.745 billion) based on severity factors and tonnages of emissions, for a total cost of $15.168 billion. This result is actually equivalent to the highly unrealistic assumption that 125% of all respiratory disease costs, plus 50% of all cardiovascular disease costs, plus 75% of all non-respiratory cancer, are attributable to air pollution.

If one starts with the basic numbers for respiratory disease costs, as provided by Ridker and by Lave and Seskin, and apportions these costs properly between smoking and the urban factor, and then takes a realistic percentage of the urban factor to be caused by air pollution, the resulting cost estimates are much more reasonable.

The major conclusion of this analysis is that cigarette smoking is a far more important cause of respiratory disease than air pollution. The dollar value of these respective costs were arrived at using Ridker's estimate for the total cost to society of respiratory disease based in loss of income, hospital expenses, and other discernable economic factors. Of course, the actual dollar value of human life and health is impossible to quantify since its value, in each individual case, depends on the viewpoint of the observer; i.e. whether the affected individual is an employee or the observer himself. However, regardless of the total assigned cost of respiratory disease, the conclusion regarding the relative importance of cigarette smoking and air pollution remains valid. The dollar values given in this paper represent an estimate of the overall loss to the economy of the United States due to these factors.

Costs

One of the earliest studies of the cost of air pollution damage was the 1913 Mellon Institute study of smoke damage in Pittsburgh. This study utilized the now-standard techniques of literature survey, questionnaires, and direct observation to evaluate a variety of costs related to smoke. The total damage cost estimate was $9.9 million, or $20 per person in the city of Pittsburgh in 1913. Although this study was for a very specific situation and included only soiling and materials damage due to smoke, it is important for two reasons: 1) it established a procedure for evaluating air pollution costs which has been used many times since 1913 to estimate costs due to air pollution, and 2) the resulting cost of $20 per person has been used and misused in many subsequent studies of air pollution costs. The highly publicized value of $65 per person for the total national cost of air pollution has been arrived at by simply inflating the Mellon result by the cost-of-living increase since 1913, and the often used national cost of \$11 billion to \$15 billion is this figure multiplied by the United States population, with an additional inflation factor sometimes applied to update the \$65 per person value.

Obviously, the projection of the 1913 Mellon result to a current national estimate for all air pollution damage is completely unwarranted. More recently, several more detailed studies have been conducted in order to arrive at estimates for the national cost of air pollution damage. Ridker[14] published a book on the economic costs of air pollution, which included consideration of costs due to health effects, soiling, materials damage, esthetics, and property values. He projected that the total cost of air pollution in 1970 would be between \$7.3 billion and \$8.9 billion. The 1968 total cost has been estimated at \$8.1 billion. More recently, Barrett and Waddell[23] reported a survey of the pertinent literature up to that time and arrived at a total national cost of \$16.1 billion for air pollution damage to health, property values, materials and vegetation. They went on to assign these costs to the various pollutants according to their relative tonnage of emissions. For example, of the \$6.06 billion in total health costs, they assigned costs to SO_2 and particulates solely on the basis of their relative emissions, and since SO_2 accounts for 54% of the total emissions of SO_2 and particulates combined, the conclusion was drawn that SO_2 alone causes \$3.272 billion in health damage. This conclusion is based on two incorrect assumptions: 1) that air pollution damage to health is due to SO_2 and particulates alone and 2) that the toxicity of SO_2 and particulates are the same. Both of these assumptions are without justification.

The assignment of damage solely on the basis of tonnages of emissions is unjustified because differences in toxicity and exposure are not taken into account. Clearly, an approach which accounts for these differences is needed to arrive at reliable estimates of total air pollution damage by specific pollutants. In order to apportion costs among the separate pollutants, nation-wide total costs for air pollution damage to health, materials, plants, animals, and reduction in visibility are developed from a survey of the latest literature on these costs.

A method has been developed by which the costs of air pollution damage are evaluated from the exceedence of damage thresholds and the application of severity factors for each pollutant-effect interaction. The damage thresholds were assumed to be the air quality standards, since accurate thresholds have not yet been determined. Total annual damage cost estimates for each of five pollutants are: Particulates - from \$1.0 billion to \$4.7 billion, surphur dioxide - from \$0.3 billion to \$1.7 billion nitrogen dioxide - \$0.1 billion to \$0.5 billion, oxidants - \$0.5 billion to \$1.5 billion, carbon monoxide - \$0.06 billion to \$0.3 billion; for a total 1970 nationwide air pollution cost of from \$2.0 billion to \$8.7 billion[5].

Control

One set of emission regulations (for Georgia) based on using tall stacks for SO_2 control is described as follows:

SO_2 emissions from any source is restricted to a value of $400F\,(h_s/300)^3$ pounds per hour for sources with weighted average stack heights (h_s) less than 300 feet and to $400F\,(h_s/300)^2$ pounds per hour for sources with stack heights h_s greater than 300 feet. The factor F is taken to be 1 for urban fuel burning sources and all other kinds of sources, 0.8 when 2 or more fuel burning sources have a heat input of more than 500 million BTU/hour and which burn fuel containing more than 1 percent sulphur are located in an urban area, 2 for rural fuel burning sources having a heat input less than 10,000 million BTU/hour, and 3 for rural fuel burning sources with a heat input greater than 10,000 million BTU/hour. A source is considered to be urban if it is located within 5 miles of a city with a population of 50,000 or more. Similar stack height dependent emission regulations were also applied for particulates, to be applied in addition to the restriction by the boiler curve or process weight rate chart. The SO_2 emission regulations, when tested under 1975 projected conditions, were found to successfully attain the state SO_2 ambient air quality standard (43 $\mu g/m^3$ annual mean), which is more restrictive than the Federal secondary air quality standard (60 $\mu g/m^3$ annual mean). The annual air quality standard for particulates and the short term SO_2 and particulate air quality standards, as estimated by the AQDM statistical model, were also found to be achieved satisfactorily.

As the Georgia SO_2 emission regulations are constructed, a source which is not in compliance with the regulations (and which does not burn more than 3% sulphur fuel), can come into compliance by four alternative methods; using lower sulphur fuel, installing SO_2 scrubbing equipment, constructing a taller stack, or a mixture of SO_2 reduction and taller stack. The present SO_2 regulations are formulated entirely in terms of the stack height dependent emission regulations, however additional regulations in the form of boiler curves and process weight rate charts for SO_2 can also be developed as soon as the uncertainties of SO_2 removal equipment or availability of low sulphur fuel are adequately resolved.

The stack height dependent emission regulations for the State of Georgia are unique, but in view of the lack of acceptable alternate control measures to achieve the air quality standards on schedule, were considered to be necessary. Engdahl, in a critical review commissioned by the Board of Directors of the Air Pollution Control Association, considered the various possible SO_2 control strategies and concluded that "While it is recognized that the ultimate aim of the current regulations is to limit the overall emission of SO_2 into the atmosphere, the immediate goal is to assure that ambient air quality standards are attained. In view of the lack of proven methods or processes for removing SO_2 from flue gases, explicit consideration should be given to encouraging the use of tall stacks, where appropriate, as an interim approach to help reduce the ground level concentration of SO_2." Engdahl further states, "Judging from the failure of supposedly promising SO_2 removal processes in recent years, many of the current experiments can also be expected to fail. This is the nature of research .... Meanwhile, tall stacks have been shown both here and abroad to be effective in reducing the concentration of SO_2 in the vicinity of large plants, and the public will be benefited if tall stacks are encouraged as an interim measure until reliable removal processes are available."

A primary factor influencing the decision to utilize a stack height related standard to meet ambient standards was the necessity of achieving this goal by mid-1975. The State of Georgia feels, as do others, that there are sound reasons to prefer actual reduction of SO_2 emissions. This is presently accomplished by limiting the sulphur content of fuels, based on boiler input capacity. When the use of SO_2 removal devices and/or fuel desulfurization methods are reasonably proven and available, the use of such technology is to be considered and put to use where needed or beneficial. In the meantime, use of tall stacks is a method proven effective in achieving air quality standards. When removal devices are added at later dates, the existing tall stack will allow continued air quality improvements, and a minimum acceptable air quality even during removal equipment breakdowns and adverse meteorological conditions.

The Georgia SO_2 emission regulations have been subjected to further diffusion analysis by the PEDCO Corporation (under EPA sponsorship), and it was confirmed that compliance with the Georgia SO_2 emission regulations would insure attainment of the air quality standards. However, the legal status of the Georgia tall stack standard is somewhat uncertain, since it is currently being challenged in court by the Natural Resources Defense Council (NRDC). The position of the courts is also unclear. In the "Findings of Fact" in the case of Commonwealth of Pennsylvania vs. Pennsylvania Power Company (Case No. 2 - 1972 - Equity, in the Common Pleas Court of Lawrence County, Pa.), the court stated that "The utilization of high stack technology as a method to improve ambient air quality, which is the ultimate goal of Pennsylvania's regulations, has demonstrated value." On the other hand, several other legal actions with regard to SO_2 compliance to regulations which would require SO_2 scrubbing, as summarized by Snyder (1973), have ended with varying results: compliance being required, complaince being postponed, or no action being taken.

The alternative to using tall stacks to meet the air quality criteria on schedule may well be to postpone achieving the air quality standard. The Industrial Gas Cleaning Institute submitted to EPA hearings a statement concerning the achievability of the SO_x compliance schedules through the use of SO_2 scrubbing equipment. The statement said in part: "In view of the practical design, manufacturing and construction problems, the proposed (SO_x compliance) schedules cannot be met. The final compliance should be set back until at least July 1,1980 and compliance should be on a staggered basis." The official position of EPA as handed down in its "supplementary controls" policy is to revoke the annual SO_2 secondary air quality standard and to allow selective use of air-dispersion procedures to control pollution from industrial sources threatened with shut-down because of air quality standards. The new supplementary controls proposal would ban the use of tall stacks, beyond those considered "good engineering practice," as a control strategy, and defines "reasonable time" for meeting primary ambient air standards called for in the clean Air Act as the time required to design, fabricate, and install "reasonably available control technology."

These actions which delay the attainment of the primary and secondary air quality standards have been brought about or worsened by the present energy crisis, with its resultant shortages of low sulphur fuel. In contrast, the tall stack standard in Georgia has meant that the decreased supply of low sulphur fuels has resulted in little or no change in the compliance schedules for SO_2 sources in Georgia, and the primary and secondary air quality standards will still be met on schedule by 1975. Since the Georgia regulations allow power plants to burn coal with up to 3% sulphur, the citizens of Georgia will continue to have an adequate supply of power. Most states have more restrictive regulations which result in a shortage of electric power since high sulphur coal cannot be burned.

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FINAL REPORT

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COMPARATIVE EVALUATION OF SOLAR, FISSION, FUSION, AND FOSSIL ENERGY RESOURCES

PART V

CONCLUSIONS AND RECOMMENDATIONS

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"Over periods of many millions of years plants covered the earth, converting the energy of sunlight into living tissue, some of which became buried in the depths of the earth to produce deposits of coal, oil, and natural gas. During the past few decades Man has found many valuable uses for these complex chemical substances, manufacturing from them plastics, textiles, fertilizers, and the varied end products of the petrochemical industry. Each decade sees increasing uses for these products. Coal, oil and gas are non-renewable natural resources which will certainly be of great value to future generations, as they are to ours.

However, Man has found another use for these valuable chemicals from the earth, a use other than the creation of the products that add so much to our standard of living. That is to burn them. To burn them in huge and ever increasing quantities to power the machines of society and provide heat. They are being burned at such an incredible rate that in a few short decades the world reserves of natural gas may be depleted, decades later the oil will be gone, and in a century or two the world will also be without coal. Undoubtably sussessive generations of humanity after that time will decry the excesses of the present generation in selfishly destroying these valuable resources without regard for the welfare of their decendents.

The rapid depletion of non-renewable fossil resources need not continue, since it is now or soon will be technically and economically feasible to supply all of Man's energy needs from the most abundant energy source of all, the sun. Sunlight is not only inexhaustible, but it is the only energy source which is completely non-polluting. The land area required to provide all our energy is a small fraction of the land area required to produce our food; and the land best suited for collecting solar energy, rooftops and deserts, is the land least suited for other purposes. It is time for the United States, which led the world in the development of atomic energy and in putting men on the moon, to mount an equally massive effort to usher in the Solar Age. With such a massive effort our country can offer the world the technology for the economical utilization of solar energy in all its varied forms - photovoltaic, direct solar-thermal, renewable fuels, ocean thermal, and winds. Then we can conserve our valuable non-renewable fossil resources for many future generations to enjoy, and we can all live in a world of abundant energy without pollution".[1]

Nuclear energy will be increasingly important in the coming decades, and should also be pursued with utmost emphasis placed on safety and environmental concerns. Waste heat can be used productively in northern climates. Possibilities for disposing radwaste in space away from the earth should be pursued. Nuclear reactors can provide power in large chunks, and can propel large ships and submarines. Nuclear and solar together, and if necessary solar alone, can eventually supply all of Man's energy needs.

The adverse environmental impacts of continued fossil fuel combustion are well known, and may be even more far reaching than currently thought. The air pollution choaking many of our cities is almost entirely from the combustion of fossil fuel. Coal mining is a hazardous, unhealthy occupation and many people have lost their lives extracting these materials from the depths of the earth. Oil spills have contaminated beaches and killed wildlife. Several oil spills, releasing between 10,000 tons and 100,000 tons of oil, have had a strongly adverse effect on the ecology of the area where they occurred. Oil is toxic to many marine organisms. Worldwide, about a million tons per year is spilled from various oil operations, and in the

U. S. alone another million tons of waste motor oil is dumped annually. Except for obvious localized effects when major spills occur, it has not known what the long term effect of this continued large scale dumping will be. The author once had his home destroyed by the rupture of a tank of butane gas. But in addition to these known safety and environmental hazards, the combustion of fossil fuels is causing a increase in the carbon dioxide content of the atmosphere, which could cause major worldwide climatological changes over the next few decades.

Carbon dioxide is normally not considered a pollutant since it occurs naturally in the earth's atmosphere. Huge quantities of CO_2 have been released into the atmosphere during the past few decades from the combustion of fossil fuels. It is the only combustion product whose increase in the atmosphere has been documented on a worldwide basis. Precise measurements by C D Keeling of the Scripps Institute of Oceanography showed that the carbon dioxide content increased by six parts per million between 1958 and 1968. It appears that, since 1860, when fossil fuels began to be burned in large amounts, the carbon dioxide concentration in the atmosphere has increased from 290 ppm to about 320 ppm. Reasonable projections indicate an increase to about 400 ppm by the turn of the century and 540 ppm by 2020.[2] The concentration could rise as high as 1500 ppm during the next century.

Carbon dioxide is not expected to have any direct toxic effects on man or animal life at these levels, although no long-term studies have been conducted. Many types of plants have been found to grow better with increased levels of carbon dioxide in greenhouses. The major effect of the CO_2 increase will be on the thermal balance of the earth.

CO_2 has strong absorption levels in the infrared region between 12 and 18 microns. This is the spectral region where most of the thermal energy radiating from the earth into space is concentrated. The increased CO_2 increases atmospheric absorption of this radiation, and it is reradiated at the much lower temperature of the upper atmosphere. This is known as the "greenhouse effect". CO_2 does not affect the solar energy received by the earth, but reduces energy radiated from the earth, so the result is an increase of the earth's temperature. Several investigators have calculated what this temperature rise would be. In 1956 Plass[3] calculated the effect of doubling the CO_2 content of the atmosphere and predicted a rise of 3.6°C. More recently, Manabe and Wetherald performed more extensive calculations and predicted that an increase in CO_2 content from 300 to 600 ppm would increase the average surface temperature by 2.36°C, assuming fixed relative humidity and average cloudiness. A worldwide temperature increase of this magnitude would be expected to cause considerable melting of the polar ice caps, resulting in a 100 to 200 foot rise in the level of the oceans. This would cause most coastal cities to be flooded.

There is also some concern about what is called the multiplier effect. The oceans contain 60 times as much CO_2 as the atmosphere, and this CO_2 is in equilibrium with the atmosphere at the present temperature of the oceans. If doubling of the atmospheric CO_2 causes a warming trend which results in an increase of the temperature of the oceans, then the solubility of CO_2 in the oceans is reduced. Thus, warming of the oceans could cause large additional amounts of CO_2 to be released, causing the temperature to increase still further.

The problem of predicting the effects of energy production on the thermal balance of the earth is complicated even further, due to the effects of particulates. There is some uncertainty at present as to whether particulates released into the atmosphere tend to increase or decrease the temperature of the earth, but most researchers believe that particulates tend to lower the earth's temperature by scattering sunlight back into space. Barrett[4] et al. used an estimate of 4 million tons for particulates in the atmosphere and calculated the global mean temperature to be 0.8°C below what it would be in the absence of any particles. Doubling the particulate loading would result in a further decrease of 1°C. Thus, if aerosol and CO_2 concentrations were to increase at the same rate, one might expect a net warming trend. If the aerosol doubling time is much shorter than that for CO_2, a cooling trend could result. The effects of high altitude particulate emissions by jet aircraft introduce additional uncertainty, since their effects are difficult to take into account.

Thus, the air pollution resulting from energy production has a wide variety of effects on man and on his environment. Techniques are being developed and applied for reducing emissions of sulfur dioxide, the nitrogen oxides, particulates, carbon monoxide and hydrocarbons. The release of vast quantities of CO_2 into the atmosphere will continue unabated as long as fossil fuels are burned for large scale energy generation.

In view of these and other considerations, it is recommended that the United States establish the goal of eliminating the combustion of fossil fuels in this century. In order to achieve this goal, while providing abundant supplies of energy to the people of this country, the following actions should be taken.

1. Accelerate the construction of nuclear reactors and the development and deployment of nuclear breeder reactors without sacrificing safety. Each vender should be allowed to market several AEC-approved standardized plants which can be erected on a site within 4 years of contract initiation.

2. Launch a crash program to develop and install solar energy systems with a funding level of about half that devoted to nuclear energy. Recommendations for the required R&D are given in Part I of this report.
3. Pursue all other energy alternatives, such as geothermal and fusion, at appropriate funding levels.
4. For the immediate energy crisis coal must be substituted for gas and oil whenever possible. Power plants should burn coal and, as an interim measure, use tall stacks for SO_2 control.[5]

If these actions are taken, we can have all the energy we need, we can become energetically self-sufficient, and we can conserve our valuable non-renewable fossil resources for many future generations to enjoy.

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